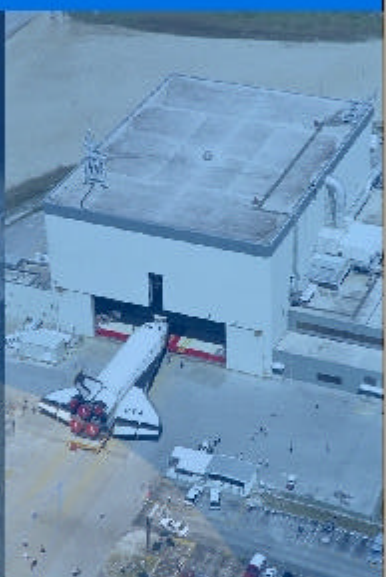
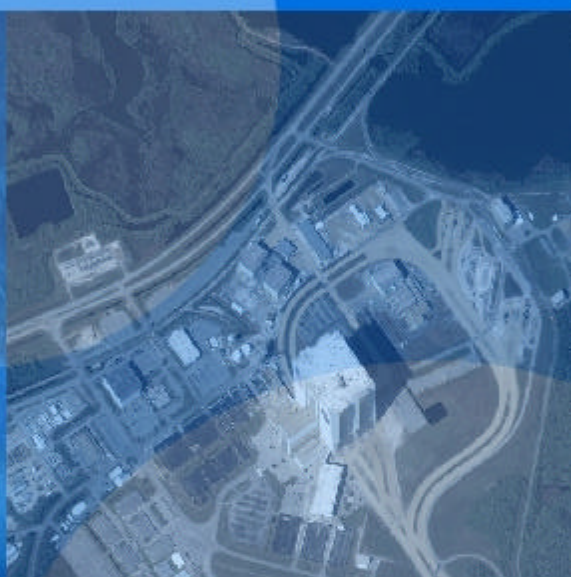
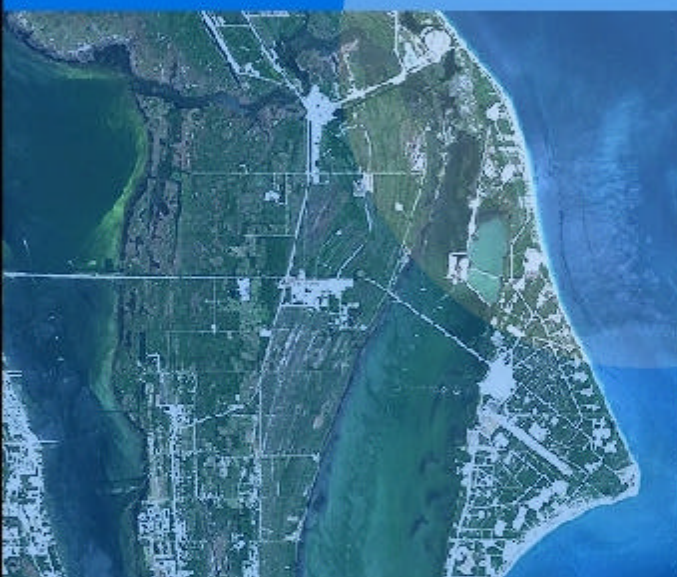




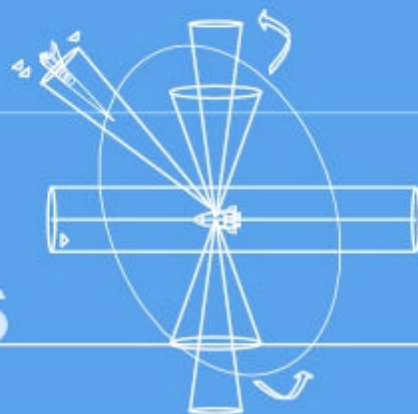
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**D4Ops**

Design for Operations



D4OPS: DESIGN FOR OPERATIONS "FROM THE GROUND-UP" OPERABILITY DESIGN AND  
MODELING FOR FUTURE REUSABLE LAUNCH SYSTEMS (RLS)

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## Foreword and Acknowledgements

The authors and sponsors of this study believe that the operational characteristics of future Earth-To-Orbit (ETO) space launch vehicles (expendable and/or reusable) are key drivers that will determine program viability. Yet there seems to be lack of appreciation of this fact from the space launch vehicle design community, and specifically from the performance-oriented design disciplines. The following study is presented as a remedy to this problem by making the performance-driven design community aware of the operational implications of their top level design choices on operationally driven Figures of Merit (FOM). The specific intended audience for this report includes both space operations analysts and space launch vehicle engineering designers during the conceptual or Pre-Phase A/Phase A stage of design. At this critical stage, top level parameters are being traded against each other in order to achieve an initial converged (and possibly optimized) design point. It is hoped that this initial effort can stimulate dialogue between the operations side and design side of the space conceptual design community.

The authors acknowledge specific support of this study through the Systems Engineering Office at NASA's Kennedy Space Center (KSC) in Florida. Special acknowledgements are due to Edgar Zapata, Carey McCleskey, and Russ Rhodes. Technical assistance provided by Tom Hoffman and Mike Squire of NASA KSC is also appreciated. Additional regard is also expressed to various Space Shuttle sub-systems experts interviewed during the course of this project. Insight gained into the detailed operation of such sub-systems was invaluable in understanding the operational complexity of the only fleet of reusable launch vehicles (RLVs).

The authors also acknowledge related work performed concurrently with this study entitled "Facility and Ground Support Equipment (GSE) Operations Analysis (FGOA) for Future Space Transportation Systems" and also supported by the NASA KSC Systems Engineering Office and Edgar Zapata. Appreciation for technical assistance on this separate project is given to Joe Brown of Construction Cost Consultants and William J. Murray of Hanson Professional Services Inc.

# Executive Summary

## STUDY CONTEXT

Future generations of reusable space launch systems are constantly being envisioned to replace the Space Shuttle. The metrics of performance, cost, safety, and operations are meticulously scrutinized for these new concepts. Yet, a satisfying design that optimizes all metrics may not exist. Compromises have to be considered in such designs, between the “physical” parameters such as gross and dry weight that determine feasibility and the “economic” parameters such as recurring operations cost that determine viability. In the quest to determine the most optimum design too often the performance experts of such concepts, who normally are at the lead of the design process, do not concern themselves with the impact of their design assumptions upon economic metrics. Their intuition is based upon collective experience in optimizing the performance half of the equation. It is in this environment that the following study takes place.

This study seeks to examine the differences that result when both performance and operations-oriented intuition are combined in the conceptual design of a reusable launch system (RLS) for space applications. Objectives for this study include examining the relative merits of these D4Ops approaches (singly and in combination) and more importantly providing a unique case study of how this operational intuition can lead towards better designs. This intuition can be described as the assumptions one gravitates towards in the conceptual design of a system. These can include factors as diverse as the number of engines on each stage or the type of Thermal Protection System (TPS) material to be used on the vehicle. This study uses a systematic approach to represent such design intuition. This includes the use of various “design for operations” (D4Ops) approaches that represent distinct choices about the nature of the launch system. A set of specific D4Ops approaches to be used in this study are developed through data-mining Space Shuttle orbiter processing information from NASA’s Kennedy Space Center (KSC). Depending upon feasibility, these approaches are applied to three different launch vehicle examples (or contexts). Some of these contexts are based on existing NASA reference designs and include near (first launch in 2010, Context 1), mid (first launch in 2015, Context 2), and far (first launch in 2025+, Context 3) term examples. Modeling and simulation then determine metrics that define the performance feasibility and economic viability of each context. A baseline system design is initially developed for the eventual application of such D4Ops approaches. Specific lessons about the merits of these D4Ops approaches, as obtained from the first two contexts, are applied to the far term context.

## STUDY FINDINGS

Relevant findings derived from this study include:

- The D4Ops approaches chosen for this study had a wide variety of impacts on the system.
- Application of most of these D4Ops approaches result in systems that performed better operationally (in terms of lower recurring operations cost per flight and turnaround time) at a cost of having worse performance. Application of these approaches generally resulted in systems with heavier dry and gross lift-off weights (GLOW) that required more development funding with higher flight unit acquisition costs.
- While many D4Ops design features do impose performance (i.e. weight) penalties, some approaches can provide operational benefits with only slight performance penalties.
- The D4Ops approaches chosen for this study were developed through a combination of qualitative and quantitative processes.
- It took extensive time and effort to develop and apply the first foundations of such a D4Ops intuition. As more contexts were examined, this process became easier. As the project progressed the study group was more and more concerned about using the D4Ops design intuition that was developed from each previous Context. Thus by Context 3 this study group was readily cognizant of the impact of certain design decisions upon operational metrics of interest. For example, as the project further progressed the impact of reducing to a complete battery power storage system became apparent. Yet even at the end of the study, there was still some hesitancy in taking the D4Ops philosophy to its logical conclusion.

- The portion of the Root Cause Analysis (RCA) database used in this study, based upon Space Transportation System (STS) orbiter processing information from NASA KSC, has some data integrity issues. The work hours in the database may not be reflective of actual man hours on each task. The data should be updated to reflect both the breadth of missions (currently only includes data mainly for the STS-81 flight) and the depth of work required all throughout the organization for such a flight.
- Constraints were imposed by the pre-selection of Contexts 1 and 2. The top level architecture assumptions inherent in these two contexts, an Orbital Space Plane (OSP) and Two-Stage-To-Orbit (TSTO) RLS, precluded some approaches from being applied. Conversely, this actually may have been beneficial in order to show the discrepancy of current performance-oriented design intuition and the influence of a D4Ops-oriented approach.
- Even given flexibility in choosing Context 3, it was potentially too constrained to be able to handle all of the D4Ops approaches developed from the RCA database.
- It is recognized that the Context 3 RLS is an easier concept to operate given the single stage nature of the architecture. There is no implication made here that such Single-Stage-To-Orbit (SSTO) systems are the most optimum. The SSTO option was chosen to include a vastly different context than that seen in Contexts 1 and 2.
- Design discussion and data transfer issues were made easier by the co-location of both performance and operations discipline experts in the same geographic area (as performed by the authors, located at the same organization).
- The conceptual level toolset is limited in its ability to model certain D4Ops design approaches.
- Reducing the number of fluids carried on a RLS is beneficial to its operability.
- Given the extensive nature of some of the D4Ops approaches on nearer term Contexts 1 and 2, it is speculated that adding such approaches to the current Space Shuttle orbiter would be very difficult and potentially vastly expensive.

## SELECTED RECOMMENDATIONS

- The results of this study should be used to integrate the D4Ops design intuition philosophy into the current conceptual design process. This could include education of the performance-oriented discipline experts of the impact of their design assumptions on operational Figures of Merit (FOMs).
- Better modeling capability should be developed to handle different operational approaches than those currently used on the Space Shuttle. There may be a need to examine the entire operational flow process for these contexts (from landing to launch) to better account for the impact of D4Ops approaches.
- Future analyses using the D4Ops philosophy should examine contexts from the same time frame for more accurate comparison of D4Ops approaches.
- Additional D4Ops approaches can be developed using similar methods of brainstorming and prioritization as described in this study.
- The Root Cause Analysis (RCA) database needs to be updated with additional data gathering and mining.
- There may be a potential to examine a more revolutionary use of the D4Ops philosophy in the design process. There may be some follow-on activity from this project that could examine how the execution of the operations discipline could be moved forward in the design process, feeding some portion of the performance closure loop. In this scenario, the operations discipline could actually help determine vehicle level characteristics such as the geometry including the outer mold line (OML).

# Chapter 1 – Background and Purpose

## 1.1 BACKGROUND

In the history of space exploration the quest for better Earth-To-Orbit (ETO) space access has been of paramount concern. The first such efforts were concerned about just proving concepts could be executed successfully. In recent times it is not sufficient to merely achieve orbit, it has become necessary for this process to be performed more safely in less time and for less cost (for expendable and reusable systems). Due to its very nature, the operational attributes of a reusable system will be a critical determinant of system viability.

The United States Space Shuttle is the world's only current operational reusable launch system (if at least partly, not including the external tank) with the attendant compromises inherent in such a designation. More than twenty years of experience has been obtained on the Space Shuttle program and this data can provide valuable insights into better ways of processing such a system. Additional experience has been obtained through the concurrent operation of expendable launch vehicles (i.e. Atlas, Delta, Ariane, Proton, etc.) and the historical knowledge of Space Shuttle precursors (i.e. X-15). This data points out critical actions that need to be reduced in the current processing flow. The Space Shuttle is by itself a great technical achievement, yet the complex nature of the system demands an equally complex and extensive operational refurbishment process. The Space Shuttle is an intricate machine, replete with various embedded subsystems in close proximity to each other that need careful scrutiny when being refurbished for the next flight. The Space Shuttle orbiter is processed in one of the three Orbiter Processing Facility (OPF) bays for approximately 80 calendar days (62 work days) with total mean integrated turnaround time of 159 days (OPF, Vehicle Assembly Building, and pad time)<sup>1,2</sup>. Such extensive processing has a direct impact upon the recurring cost of the Space Shuttle requiring a proportional increase in manpower and physical resources. The reasons for such processing requirements can be directly traced to the selection of subsystems on the architecture. Due to these selections in the early phases of design, optimistic predictions prior to the Shuttle's first flight of a large flight rate and subsequent low levels of processing have not materialized.

There are many groups within NASA who are examining the next generation of reusable launch system (RLS) concepts and architectures. The perspective of these groups is focused on the conceptual and preliminary (Phase 0 and 1 respectively, pre-Phase A or Phase A) levels of design. Specific recent examples of these design groups include the NASA Next Generation Launch Technology (NGLT) Systems Analysis group, the NASA Space Architect, the NASA Marshall Space Flight Center (MSFC) Advanced Concepts group, and the NASA Langley Research Center (LaRC) Vehicle Analysis Branch (VAB). This level of design is concerned with transition from a given set of requirements to an initial technical design of the system. The technical members of these teams traditionally originate from the performance disciplines (aerodynamics, CAD, structures, trajectory, aeroheating, weights, sizing, thermal protection, etc.). In the recent past, these groups have included other important (non-technical) disciplines such as cost/economics, safety, and operations. These additional disciplines are normally active in the latter stages of designs after the performance disciplines have executed their analyses. As the initial conception of the vehicle is developed amidst discussions of the design group, and as the subsystems are chosen, traditionally the most vocal members have been the performance discipline experts. Obviously, given their technical knowledge, this performance-oriented sub-group accepts exclusive license to select subsystems and develop the initial conception of the vehicle. The non-performance related (i.e. cost, operations, safety, and economics) discipline experts may also have valuable contributions in the initial conception of the system. Yet due to the nominal design process, wherein these simulations execute after the performance closure, the contributions of these experts are not captured appropriately. It is not a question of whether the expertise of these non-performance disciplines is heard in the design process, but when in the design loop. During the initial formulation of the concept, massive architecture-level and subsystem assumptions are fixed that will propagate throughout the rest of the life cycle.

As this evolution of the design team has progressed, so has the portfolio of metrics used to assess the viability of an RLS. The basket of metrics, or Figures of Merit (FOMs), include traditional performance metrics such as gross liftoff weight (GLOW) and dry weight but includes the even more relevant program metrics of life cycle cost (LCC), development cost, fleet acquisition cost, turnaround time or TAT (processing time after landing until the next liftoff), recurring cost per flight, facilities cost, reliability, and safety. Yet, a satisfying design that optimizes all

metrics may not exist. Compromises have to be considered in such design, between these physical/performance-related parameters and the operational/safety/economic parameters.

## 1.2 PURPOSE

Often the performance designers of space launch systems do not concern themselves with the economic and operational impact of their design assumptions. Subsequently, there is scant linkage between appropriate subsystem technology choice and the impact on overall vehicle level metrics. It is in this environment that the following study takes place. As experience with the Space Shuttle has proven, operations will be the main driver in determining success over the life cycle of an RLS program. Reductions in turnaround time and recurring cost can result in increases in mission availability of specific space launch architectures, resulting in a lower overall fleet size requirement. Operationally better space launch systems (with reduced turnaround time, recurring operational cost, and facilities cost) can be obtained through several possible paths: reduce capability, add more facilities and manpower, or design the architecture from the outset to be more operable.

The goal of this study is to extrapolate insights (or approaches) gained from Space Shuttle processing experience that result in operational benefits and apply them to various future reusable launch system (RLS) case studies (or contexts). The authors seek to expand the design intuition of conceptual launch vehicle architects to include appreciation of operationally-oriented design approaches. Performance-oriented designers should be cognizant, if even qualitatively, of the impact of their design assumptions on the ultimate metrics of the system. The authors do not ask for a revolution in making such cost and operational concerns paramount over performance-related metrics, but to be placed in a more relevant position of importance in the design process.

These “design for operations” (D4Ops) choices or approaches are determined from data-mining NASA Space Shuttle orbiter processing information. There is a substantial amount of raw data available that describes the quantitative aspects of processing the Space Shuttle (especially during the turnaround phase of the orbiter in the Orbiter Processing Facility or OPF). Examination of this data can reveal potential linchpins in such processing which could be ameliorated for a new RLS through a re-thinking of subsystem inclusion in the initial design phase. For this study, these D4Ops approaches are applied to three different launch vehicle examples (or contexts). Some of these contexts are based on existing NASA reference designs and include near (first launch in 2010, Context 1), mid (first launch in 2015, Context 2), and far (first launch in 2025+, Context 3) term examples. Modeling and simulation then determine metrics that define the performance feasibility and economic viability of each context. A baseline system design is initially developed for the eventual application of such D4Ops approaches. Specific lessons about the merits of these D4Ops approaches, as obtained from the first two contexts, are applied to the far term context.

## NOTES

1. “Spaceport Systems Processing Model, Introduction to Space Shuttle Processing, Emphasis is on Phase-A Elements to Be Modeled,” NASA Presentation by University of Central Florida, February 4, 2000.
2. “Probabilistic Operations Event Modeler of ATT1 and STS”, Dr. Alan Wilhite, The University of Alabama in Huntsville, January 2004.

## Chapter 2 – Outline of the Study

### 2.1 OVERVIEW

It is envisioned here that dramatically safer, lower cost and faster turnaround time space launch systems are possible by applying the wealth of experience gained from Space Shuttle operations. This data, while sometimes difficult to obtain, can generate specific insights and lessons learned valuable for future designs. Specific data such as the Shuttle Root Cause Analysis (RCA) adds further insight to quantifiably understand why previous reusable launch systems (RLS) have been unaffordable and why they take as long as they do to prepare for launch.

The Design for Operations (D4Ops) study is a 9-month effort by the NASA Kennedy Space Center (KSC) Systems Engineering Office, and SpaceWorks Engineering Inc. (SEI) to begin quantifying the potential benefits of diverse new operational approaches. The study aims to determine the key compromises and trade-offs between weight, cost, operations, and safety when implementing new D4Ops approaches for different space vehicle configurations and operations. The objective is to assist in defining a new and significantly enhanced understanding of multitudes of factors in a space transportation system design, all of which interact in complex and often un-intended ways. By achieving this understanding it will be possible to derive system designs for future space transportation systems that not only meet performance requirements, but which also do so affordably, safely and at high flight rates. The study leverages findings from NASA's Root Cause Analysis (RCA) project that is continuing to document driving maintenance tasks on the Space Transportation System (STS) orbiter. Using the RCA database as an anchor point, the present study developed a list of 11 proposed D4Ops approaches that have a potential to positively influence the operational figures-of-merit used to evaluate next-generation space vehicle designs (see Figure 2.1 and Table 2.1). Typical "D4Ops approaches" include: reducing overall parts count, integrating functions across subsystems, eliminating hypergolic propellants, reducing numbers of tanks and fluids, etc.

Phase I of the project entailed of determination of the specific set of D4Ops approaches to be included in the analysis. This portion consisted of data-mining the RCA database as provided by NASA KSC for linchpins in the processing of the current Space Shuttle. Review of the outputs from this database yielded such operational effectiveness (OE) attributes of the system. This was coupled with additional brainstorming by the authors, along with assistance from NASA KSC personnel, for additional approaches. Both sets of approaches yielded a total of 50+ approaches that were ranked using a Quality Function Deployment (QFD) process. Compatibility was determined for each approach combination and thus a set of 11 approaches was finalized. This number is reflective of an appropriate initial set of approaches that could be handled given the scope of this study.

Phase II of the project consisted of application of the above determined approaches on specific space launch architectures on interest (referred to as contexts). Specifically, three different space vehicle contexts (referred to as 1, 2, and 3) are used as a backdrop to the analyses conducted in the study: an Orbital Space Plane (OSP), Two-Stage-To-Orbit RLS, and a new, advanced RLS concept designed for streamlined operations (see Figure 2.2). These contexts were chosen based on NASA's current Integrated Space Transportation Plan (ISTP). The goal is to compare but not replicate previous analyses.

The authors used their multi-disciplinary conceptual design environment comprised of in-house and government/industry standard computational design tools to evaluate each context and determine the positive and negative impacts on weight, cost, performance, operations, reliability, and safety that result from the application of the proposed D4Ops approaches. For Contexts 1 and 2, baseline configurations, using a state-of-practice (SOP) design philosophy, were first created (see Figure 2.3). The numerical results were calibrated to design information available from ongoing studies at NASA and in industry-not to be competitive, but to ensure the results are relevant. Once a satisfactory baseline was established, sensitivities were conducted on each of the 11 D4Ops approaches taken individually. In addition, a single roll-up of all applicable D4Ops approaches was conducted for each context. Using multi-attribute decision-making methods, the candidate D4Ops approaches were assessed and ranked based on quantitative benefits to several key figures-of-merit. The study draws conclusions and prioritizes the most promising D4Ops approaches across the three RLS contexts in terms of their potential to positively impact ground operations costs and cycle times without detrimentally affecting weight, non-recurring cost, or vehicle safety. The

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study has concluded as of January 2004. The results and the associated D4Ops rankings will be made available to current space vehicle design teams to be used as a decision-support resource for ongoing activities.

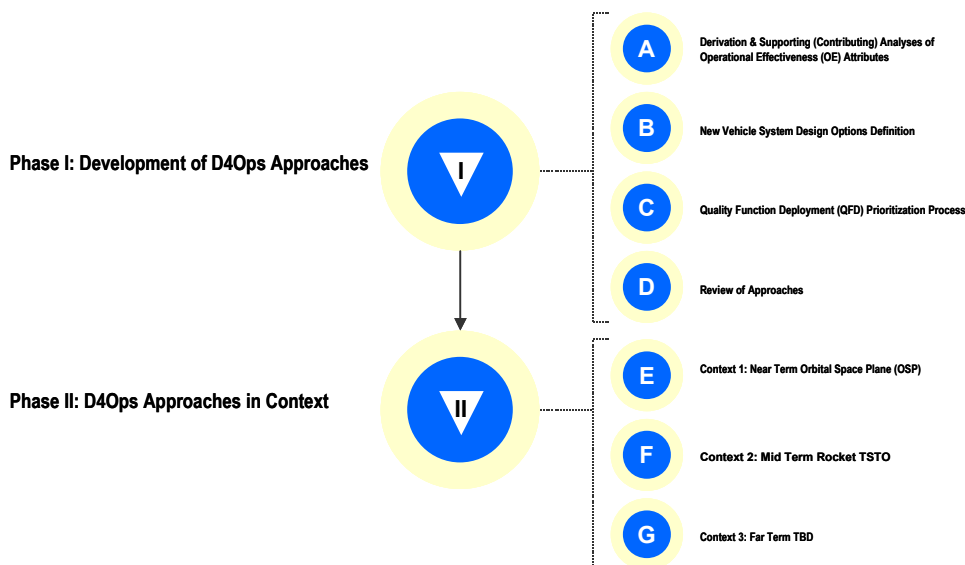


Figure 2.1. Overview of D4Ops Project

Table 2.1. Basis of Selected D4ps Approaches

Design4Ops Strategy	Work Content Potential Reduction Through Use of D4Ops Strategy (Total RCA Direct Work Contribution)	Selected Design Approach
INTEGRATE PROPULSION SYSTEMS	Liquid Propulsion Work Content (14.5% Max Contribution)	Reduce engine count (use larger, fewer engines for main/OMS/RCS, i.e. Eliminate need for separate OMS engines by using throttled MPS on-orbit)
		Eliminate all hypergols in favor of LOX/LH2 propellant combination for ACS
		Eliminate hypergols AND cryogenic ACS propellants in favor of "green" non-cryogenic ACS propellants
		Incorporate Propulsion-focused IVHM
INTEGRATE POWER MANAGEMENT FUNCTIONS	Power Management Work Content (10.9% Max Contribution)	Simpler, all-electric power and actuation system (use EMAs/EHAs at load and use high storage density batteries in place of fuel cells and APU's, replace plumbing with wiring)
IMPROVE PASSIVE THERMAL MANAGEMENT	Thermal Management Work Content (10.7% Max Contribution)	Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces
		Reduce TPS moldline penetration and repair/replacement (self-healing TPS including self-healing seals)
INTEGRATE ACROSS PROPULSION & AIRFRAME	Liquid Propulsion/Structures, Mechanisms & Veh Handling (48.2% Max Contribution)	Eliminate external aeroshell and closed compartments, Integrate structural/ aerodynamics systems and safety systems (Haz Gas and Purge, Vent and Drain-PVD) as single system, lean designs resulting in reduced or eliminated fluid systems.
INTEGRATE ACROSS PROPULSION & POWER FUNCTIONS	Liquid Propulsion/Power Mgmt (25.4% Max Contribution)	Use common fluids AND tanks for Main Propulsion System, OMS, RCS and Power
INTEGRATE ACROSS PROPULSION, PWR & THERMAL MGMNT FUNCTIONS	Liquid Prop/Power/Thermal Mgmt (36.1% Max Contribution)	Use common fluids and tanks for Main Propulsion System, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics, and ECLSS)
INCREASE OVERALL SYSTEMS RELIABILITY	Unplanned Work Content (24% Max Contribution)	Reduce parts count using highly reliable parts (vs. less reliability in the parts and higher need for redundancy as in Shuttle)

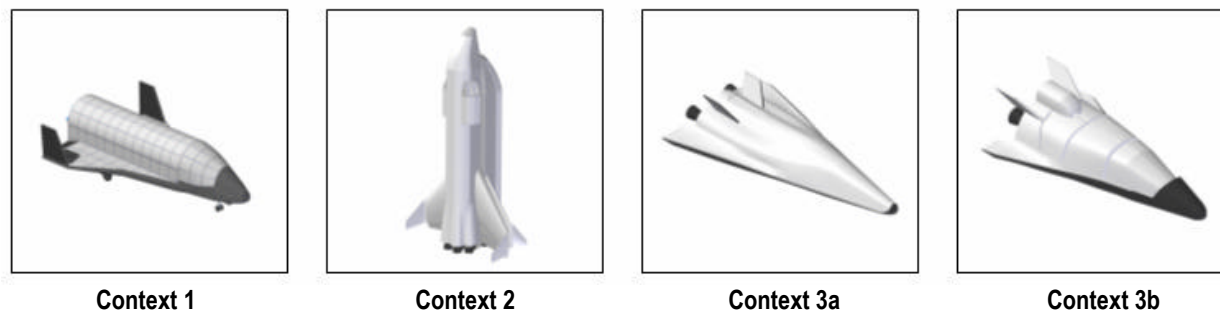


Figure 2.2. Sample Design Contexts for Operational Approaches

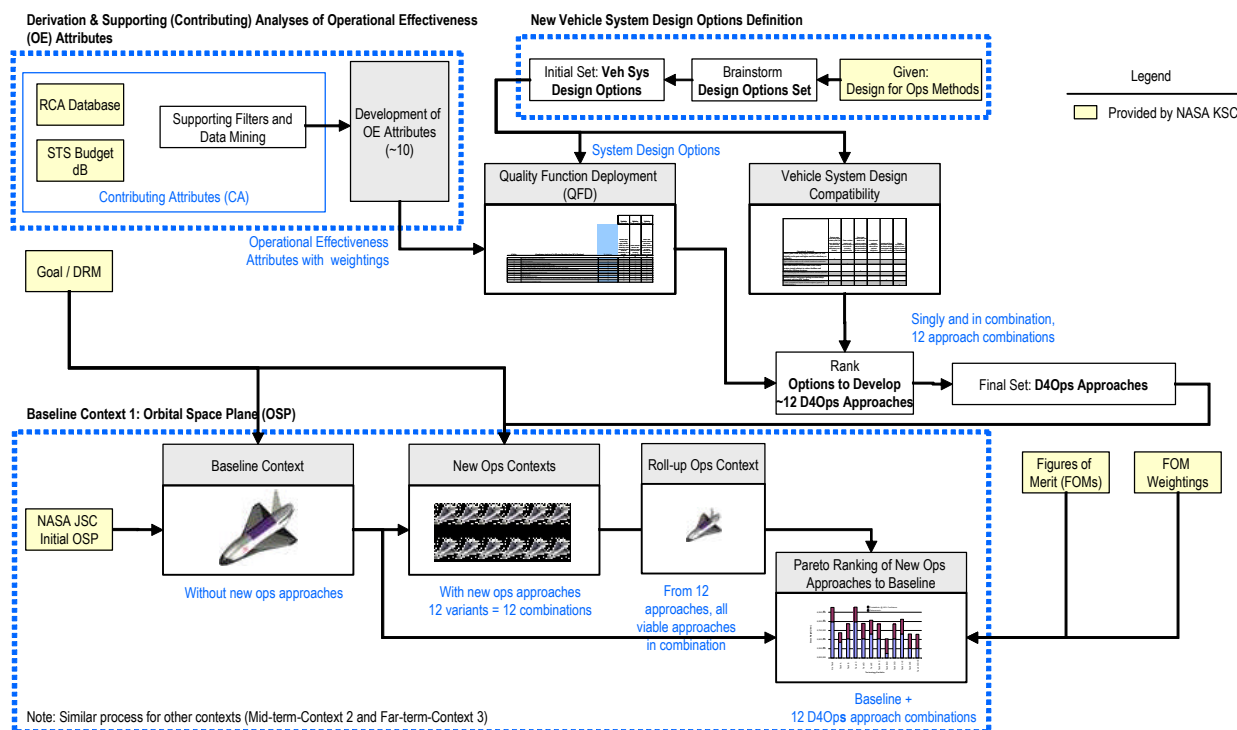


Figure 2.3. Schematic of D4Ops Approach (For Context 1)

## Chapter 3 – Root Cause Analysis Database

### 3.1 GENERAL OBSERVATIONS

One of the first tasks of the D4Ops project was the review of the NASA Kennedy Space Center (KSC) Root Cause Analysis Database (RCA DB). This database (in MS Access format) consists of various operations performed on the Space Shuttle Atlantis in the calendar years 1996 and 1997 encompassing missions STS-79 and STS-81 (with a majority of the data reflecting STS-81)<sup>1</sup>. The database can be organized by a Functional Breakdown System (FBS) that numbers the various parts of the operations. Specific functions in the database include: FBS 1.0: Landing and Recovery, FBS 2.0: Flight Element Turnaround, FBS 3.0: Flight Element Assembly, FBS 4.0: Launch Vehicle Integration, FBS 5.0: Launch, and FBS 6.0: Element Receipt and Acceptance. A large percentage of current data maps to FBS 2.0 (Flight Element Turnaround). Specific types of data include: Ground Processing Activities, Duration of Activities, Type of Activity, Activity by Sub-Systems, Causes of Activity, Planned and Un-Planned. Each type of activity in the database links to a specific number of work content hours required for the activity. These work content hours reflect the time for the entire activity but not necessarily the amount of human hours required for the activity (some activities may only require humans in the loop to start and stop the activity). Specific impressions of the RCA DB developed during this study include<sup>2</sup>:

- The “Structures, Mechanisms, Vehicle Handling” design discipline has the most associated work content hours, double the next closest design discipline.
- The modeling of new operational approaches is heavily dependent upon design decisions.
- Turnaround (FBS 2.0) is one of the most important FBS areas. There is a need to understand that this is one of the most developed FBS areas and thus contains much data.
- Modification of the raw RCA DB results with qualitative adjustments due to processing anomalies resulting from STS-79 Solid Rocket Booster (SRB) de-stack results in no change in the ranking of design disciplines.
- More focus should be placed upon operations functions identified in OPF (FBS 2.0), particularly the FBS 2.0 unplanned troubleshooting and repair, servicing, inspection/checkout, and payload integration.
- Whereas, the OPF FBS (2.0) data contains only processing information after landing of OV-104/STS-79 to Rollout for STS-81 Stacking, other FBS (3.0, 4.0, and 5.0) contain data for both STS-79 and STS-81 stacking activities.
- More of the unplanned work (in terms of hours) occurs in the first month/half of processing in the OPF, this holds specifically for the design discipline “Turnaround Unplanned Troubleshooting and Repair” for FBS 2.0 (Flight Element Turnaround) and 3.0 (Flight Element Assembly).

### 3.2 REVIEW OF DATABASE SOURCES

The RCA DB used in the study spans two specific NASA Space Shuttle Flights (STS-79 and STS-81) that involve the Shuttle Atlantis (OV-104). These were back to back flights of the Shuttle Atlantis that took place in calendar years 1996 and 1997. The source of the data is the “CAPSS Analysis Data Query” exported from the MS Access database file named “STS Root Cause.mdb” and dated Pre-Release 2 (March 2003) as received from NASA KSC. Specific events for the STS-81 flight, from the processing schedule, include<sup>3</sup>:

- Orbiter: Space Shuttle Atlantis (OV-104) from KSC Pad 39-B (39).
- Mission: 81st Shuttle Mission, 18th Flight OV-104, 5th Mir docking, 16th Night Launch, 34th KSC Landing, STS-81 was the fifth of nine planned missions to Mir and the second one involving an exchange of U.S. astronauts. Atlantis carried the SPACEHAB double module providing additional middeck locker space for secondary experiments. STS-81 involved the transfer of approximately 5,975 pounds of logistics to and from the Mir, the largest transfer of items to date. During the docked phase, 1,400 pounds of water, 1,137.7 pounds of U.S. science equipment, 2,206.1 pounds of Russian logistics along with 268.2 pounds of miscellaneous material were transferred to Mir. Returning to Earth aboard Atlantis was 1,256.6 pounds of U.S. science material, 891.8 pounds of Russian logistics and 214.6 pounds of miscellaneous material.

- Hardware: SRB: BI-082, SRM: 360T054A(Left),360T054B(Right), ET: ET-83, MLP : MLP-2 SSME-1: SN-2041 (Block I), SSME-2: SN-2034 (Phase II), SSME-3: SN-2042 (Block I).
- The SRB set used for the STS-81 flight (BI-082) was the set that was destacked for STS-79 which flew a different set (BI-083).
- Payload: Mir-Docking/5, SpaceHab-DM, SAREX-II, KIDSAT, TVIS, Biorack, CREAM, OSVS, MSX.
- Processing: OPF-3 - 9/26/96, VAB - 12/05/96, PAD - 12/10/96, TCDT - 12/17/96.
- Launch: January 12, 1997, 4:27:23 a.m. EST. Liftoff occurred on time following smooth countdown.
- Landing: January 22, 1997, 9:22:44 a.m. EST, Runway 33, Kennedy Space Center, Fla. Rollout distance: 9,350 feet (2,850 meters). Rollout time: one minute, nine seconds. Mission duration: 10 days, four hours, 55 minutes, 21 seconds. Landed on revolution 160, on the second KSC opportunity for the day.

STS-79 was the previous flight of OV-104 (Atlantis) before STS-81. This mission had several operational flows due to various SRB and weather issues. The specific timeline/processing schedule and detailed launch de-stack includes<sup>4</sup>:

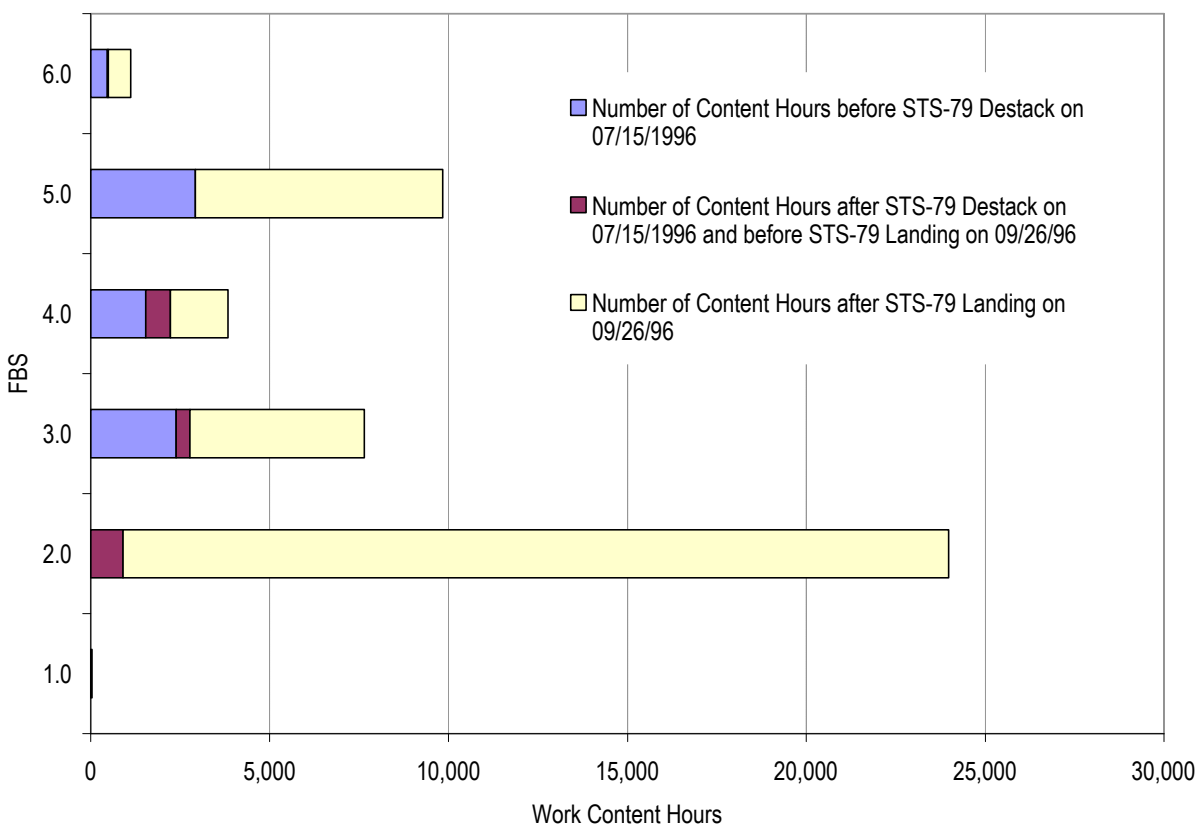
- On July 1, 1996, Atlantis was rolled out from the VAB to Pad 39A.
- On Tuesday, July 8, 1996, Mission managers decided to roll back Atlantis from Pad LC-39A to the VAB due to the projected storm track of Hurricane Bertha.
- Earlier in the week a rollback was also being considered in the event repairs will be needed to the Shuttle Solid Rocket Boosters (SRB) following the discovery of hot gas penetration of rubber insulation on the boosters for shuttle flight STS-78.
- On Monday, July 15, 1996, NASA managers decided to destack and replace Atlantis' Solid Rocket Boosters (SRB) with a new set of boosters.
- Technicians disassembling the motors of Space Shuttle mission STS-78 observed that hot gases had seeped into J-joints in the field joints of the motors. An investigation into the seepage identified the most probable cause was the use of a new adhesive and cleaning fluid. These elements were changed in order to comply with new Environmental Protection Agency regulations which reduce ozone depleting substances. The STS-79 booster set included the same adhesive so a new SRB stack built using the older adhesive will be used until the problem can be further analyzed.
- On Friday, August 2, 1996, Atlantis was demated from the original set of SRB's and transported to the OPF bay no. 3 at about 2 AM Saturday. STS-79's original SRBs are scheduled to be used on mission STS-81 after they are destacked, cleaned, inspected and restacked.
- On Thursday, August 8, 1996, STS-79's external tank was demated from STS-79's original set of SRBs. A new set of SRB's had already been stacked and destacking of the original SRB was expected to begin on the following Monday.
- Processing: Flow A, OPF - 4/15/96, VAB - 6/24/96, PAD - 7/01/96.
- Processing: Flow B (after rollback due to Hurricane Bertha and SRB problem), VAB - 7/10/96, OPF - 8/03/96, VAB - 8/13/96, PAD - 8/20/96, TCDT - 8/27/96.
- Processing: Flow C (after rollback due to Hurricane Fran), VAB - 9/04/96, PAD - 9/05/96, L-2 - 9/14/96.
- Launch: Sept. 16, 1996, 4:54:49 a.m. EDT.
- Landing: Sept. 26, 1996, 8:13:15 a.m. EDT.

This time period of the RCA database (March 7, 1996 to January 30, 1997) overlaps two Atlantis flights. There are natural questions of cleaning up to the data to accurately reflect one flight. Some outputs of the database given prior to this assessment use data for STS-79, even before STS-79 lift-off on September 26, 1996 (all the way back to March 7, 1996) to represent processing results for STS-81. This may be legitimate given the processing of the SRBs but more clarification may be required. This is important due to the fact that there is not a trivial amount of data in this time frame. Specifically such previous data, from March 7, 1996 to September 14, 1997 (two days before STS-79 liftoff), actually accounts for 8,873 (or approximately 19%) of the work hours out of a total of 46,000+ work hours in the entire data set. Table 3.1 and Figure 3.1 illustrate the breakdown on these hours in the RCA DB. The table shows the breakout of work hours for each FBS, before the STS-79 de-stack, after de-stack and before STS-79 landing, and after STS-79 landing. The amount of content hours after STS-79 de-stack on July 15, 1996 and before STS-79 landing on September 26, 1996 could be used to account for any work on the SRB de-stack once the

problem was known. Some of these hours could be legitimately applied to STS-81. Output results for the FBS 2.0 work content matrix does book-keep these separately. However, other FBS (3.0, 4.0, and 5.0) work content matrices still add disparate data for STS-79 and STS-81 processing together to represent STS-81. The main issue here resides in whether this processing time for FBS 3.0, 4.0, and 5.0 belongs to STS-81 or STS-79.

**Table 3.1. Breakdown of Work Content Data in RCA DB<sup>1</sup>**

FBS	Number of Content Hours before STS-79 De-stack on 07/15/1996	Number of Content Hours after STS-79 De-stack on 07/15/1996 and before STS-79 Landing on 09/26/96	Number of Content Hours after STS-79 Landing on 09/26/96	Total Work Content Hours
1.0	0	0	32	32
2.0	0	901	23,075	23,976
3.0	2,391	386	4,874	7,651
4.0	1,534	690	1,613	3,837
5.0	2,923	0	6,914	9,837
6.0	467	22	626	1,115
TOTAL	7,315	1,999	37,134	46,448



**Figure 3.1. Illustration of Breakdown of Work Content Data in RCA DB<sup>1</sup>**

### 3.3 DATA MINING INTRODUCTION

The RCA DB use was in the creation of a global picture in terms of the greatest drivers for each of the design disciplines. This global picture was created for the original, unorganized data set as well as the modified data set. The “Modified” data uses qualitatively derived reduction in work content hours given the non-standard processing of the architecture in STS-81 based upon the unique SRB de-stack situation in STS-79. These reductions were arrived at through discussion between the authors and NASA KSC personnel (namely on April 21 and April 28, 2003). Separately a “New” data set was developed that is based on cleaning out data in FBS areas 3.0, 4.0, and 5.0 by eliminating hours related to the processing of STS-79 which still remain in the “Original” and “Modified” data sets. This is related to the previously discussed issue of overlapping data within the database of STS-79 and STS-81 data. Subsequent sections in this report reveal the Pareto analyses performed for the “Original” and “Modified” data sets from the RCA DB. These analyses aggregate data from FBS 2.0, 3.0, 4.0, and 5.0. Aggregate work content hours, across all FBS types, were derived from the following RCA DB files: Turnaround Data\_031803.xls (FBS 2.0), Assembly Data\_031903.xls (FBS 3.0), Veh Integ Data\_031703.xls (FBS 4.0), and Launch Data\_031903.xls (FBS 5.0).

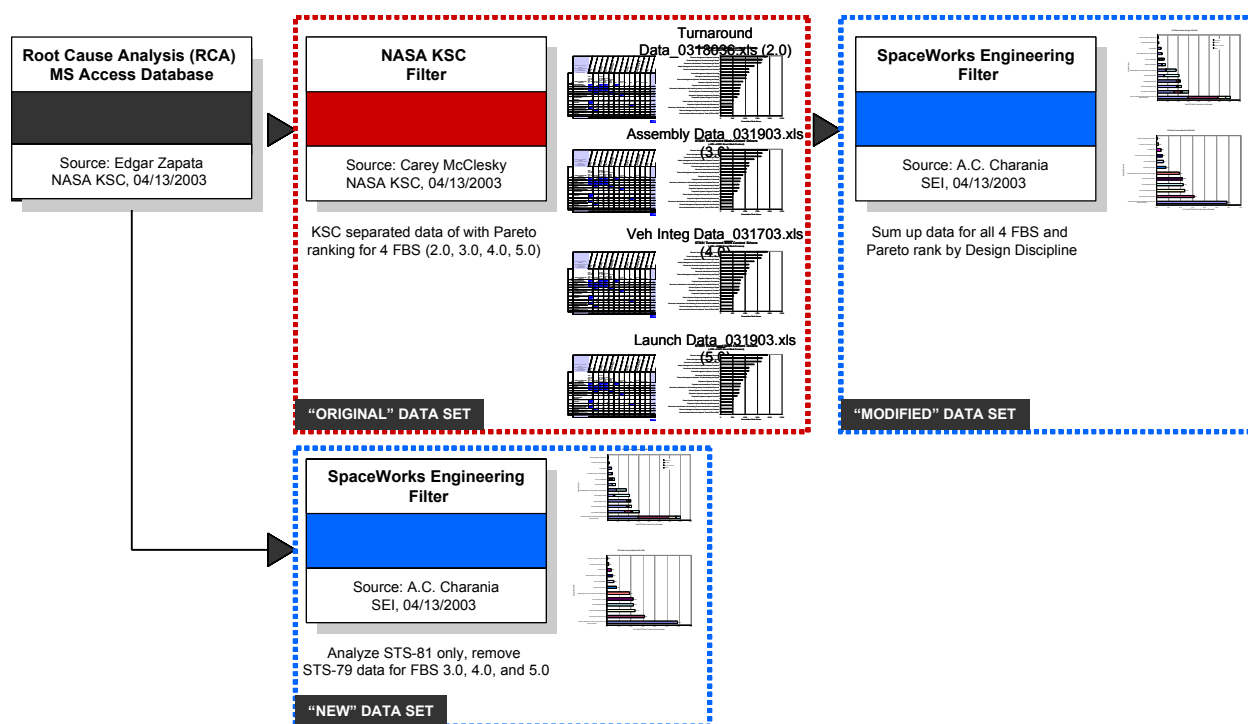


Figure 3.2. Data Extraction Process in RCA DB

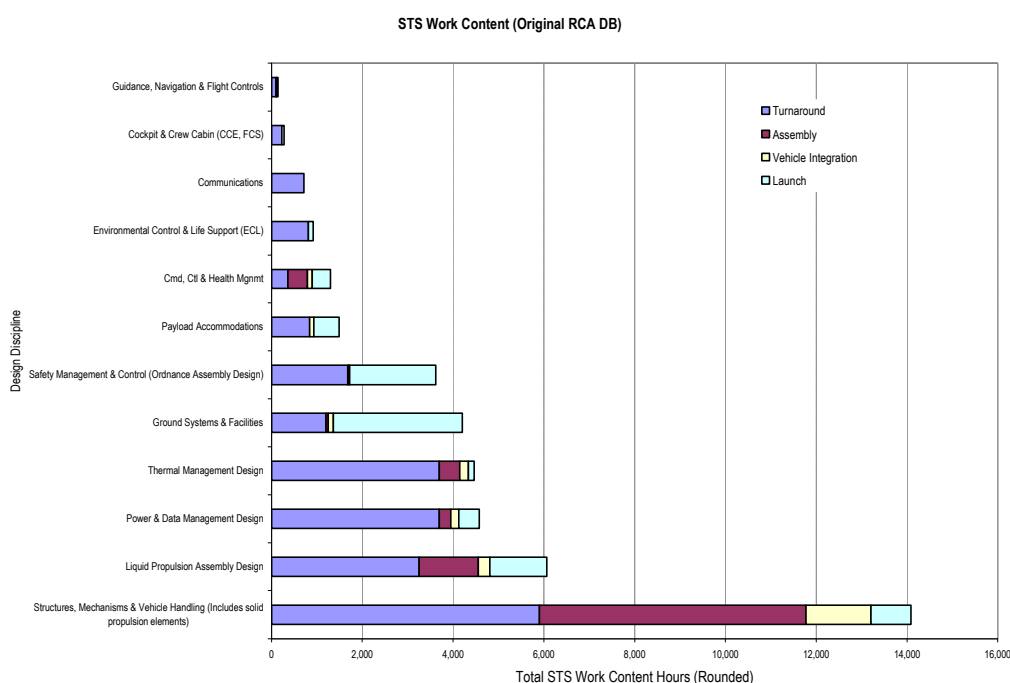
### 3.4 PARETO ANALYSIS

Pareto analysis on the RCA DB extends for each design discipline across FBS 2.0, 3.0, 4.0, and 5.0 (Figure 3.3 to 3.6). This was performed for the “Original” and “Modified” data sets. Figures 3.3 and 3.4 reflect the rankings for the “Original” data set. Figure 3.5 illustrates the ranking for the “Modified” data set and Figure 3.6 shows the comparison between the “Original” and “Modified” data sets. These charts illustrate the total amount of work in the entire database, as broken out by design discipline. Previously this was broken out by each FBS only. It was determined that an aggregated analysis may provide a different view of the data. The modified data reflect qualitatively arrived at reductions in the work content hours for specific sub-functions to account for assumed processing anomalies in STS-81 RCA DB data. These were due to anomalies related to de-stacking of SRBs in VAB with 2 roll-outs to the PAD in STS-79 that required a switch out and modification of those SRBs to STS-81. Such

activity added to “Unplanned” activities assumed to be overestimating “typical” flows. Specific adjustments made to clock hours in RCA DB for particular these sub-function hours include:

- 3.03 reduced by 50%
- 3.05 reduced by 50%
- 4.01 reduced by 25%
- 4.03 reduced by 25%
- 4.05 reduced by 50%
- 5.02 reduced by 50%

Generally, the effect of these modifications to the original data set did not change the order of the rankings of the number of hours devoted to one or another design discipline. The “Structures, Mechanisms, and Vehicle Handling” Design Discipline retained the highest number of hours from the data set.



**Figure 3.3. Pareto Distribution of STS Work Hours: Original RCA DB Data Set**

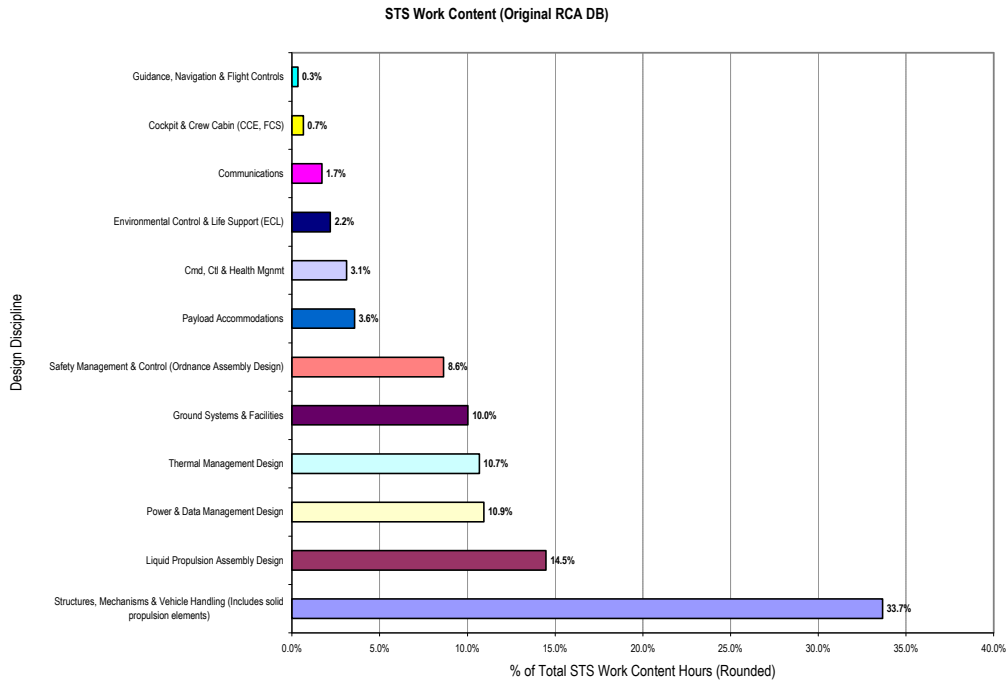


Figure 3.4. Pareto Distribution of STS Work Percentages: Original RCA DB Data Set

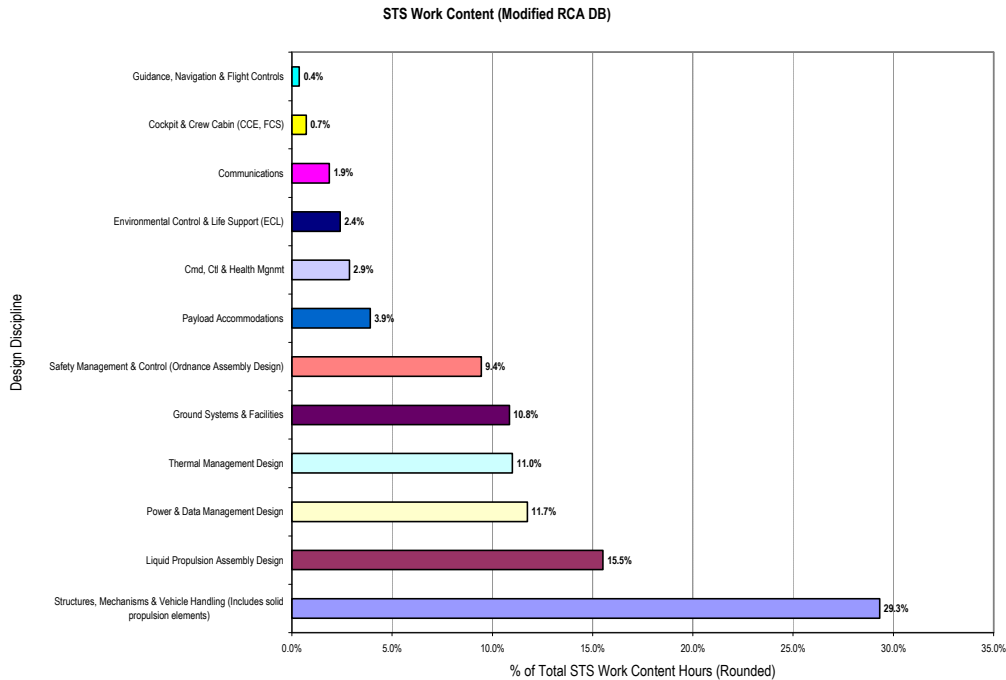
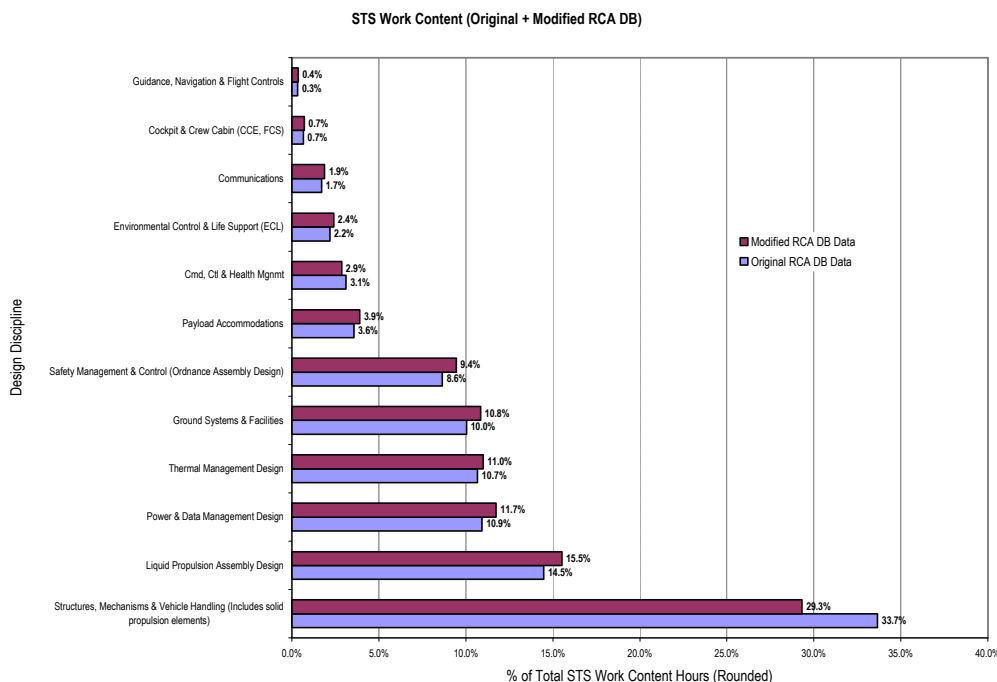


Figure 3.5. Pareto Distribution of Work: Modified RCA DB Data Set



**Figure 3.6. Pareto Distribution of Work: Original + Modified RCA DB Data Set**

### 3.5 DETAILED FUNCTIONAL BREAKDOWN STRUCTURE (FBS) ANALYSIS

Subsequently, more detailed analysis was performed on some of the RCA DB data, specifically related to FBS 2.0 and 3.0. Specific attention was paid to unplanned processes performed in these two areas, known as “Unplanned Troubleshooting and Repair” and accounted for in FBS 2.08 and 3.05. Tables 3.2 to 3.5 show the chronological breakout of work content hours from the RCA DB and the number of hours broken out by design discipline. Figure 3.7 indicates more unplanned activity in the first month of processing in the OPF than in the later stages for both FBS 2.0 and 3.0. Table 3.3 reveals for FBS 2.0 that the “Power Management” design discipline is the source of the most unplanned activity, followed closely behind by the “Structures, Mechanisms, Vehicle Handling” design discipline. For FBS 3.0 the “Structures, Mechanisms, Vehicle Handling” design discipline is the most important source for unplanned activity.

**Table 3.2. Chronological Breakdown of Work Content for FBS 2.0 for "Turnaround Unplanned Troubleshooting and Repair" (FBS 2.08)**

MONTH	HOURS
SEP	373
OCT	3,294
NOV	2,257
DEC	58
JAN	6

**Table 3.3. Design Discipline Breakdown of Work Content for FBS 2.0 for "Turnaround Unplanned Troubleshooting and Repair" (FBS 2.08)**

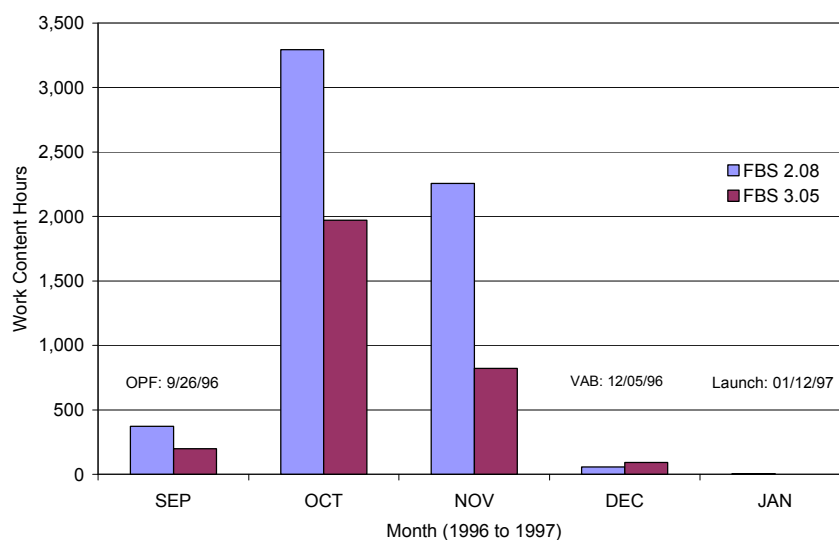
DESIGN DISCIPLINE	HOURS
Cockpit & Crew Cabin Total	4
Safety Management & Control Total	10
Guid, Nav & Ctl Total	26
Environmental Ctl & Life Spt Total	56
Communications Total	98
Cmd, Ctl & Health Mngmt Total	210
Propulsion Total	454
Ground Systems & Facilities Total	752
Thermal Management Total	1,045
Structures , Mechanisms, Veh Handling Total	1,651
Power Management Total	1,682

**Table 3.4. Chronological Breakdown of Work Content for FBS 3.0 for "Assembly Unplanned Troubleshooting and Repair" (FBS 3.05)**

MONTH	HOURS
SEP	200
OCT	1,971
NOV	823
DEC	93

**Table 3.5. Design Discipline Breakdown of Work Content for FBS 3.0 for "Assembly Unplanned Troubleshooting and Repair" (FBS 3.05)**

DESIGN DISCIPLINE	HOURS
Propulsion Total	8
Ground Systems & Facilities Total	22
Cmd, Ctl & Health Mngmt Total	128
Thermal Management Total	252
Structures , Mechanisms, Veh Handling Total	2,677



**Figure 3.7. Chronological Breakdown of Work Content for FBS for "Assembly Unplanned Troubleshooting and Repair" Design Discipline for FBS 2.08 and 3.05**

## NOTES

1. "CAPSS Analysis Data Query" exported data from RCA Access database file named "STS Root Cause.mdb" and dated Pre-Release 2 (March 2003), Work Content Matrices from Carey McCleskey at NASA KSC, (April 21 2003) that included: Turnaround Data\_031803.xls (FBS 2.0), Assembly Data\_031903.xls (FBS 3.0), Veh Integ Data\_031703.xls (FBS 4.0), Launch Data\_031903.xls (FBS 5.0).
2. The entirety of the RCA DB and associated documentation can be obtained at:  
[http://science.ksc.nasa.gov/shuttle/nexgen/RCA\\_main.htm](http://science.ksc.nasa.gov/shuttle/nexgen/RCA_main.htm)
3. NASA Kennedy Space Center Science, Technology and Engineering page,  
<http://science.ksc.nasa.gov/shuttle/missions/sts-81/mission-sts-81.html>.
4. NASA Kennedy Space Center Science, Technology and Engineering page,  
<http://science.ksc.nasa.gov/shuttle/missions/sts-81/mission-sts-81.html>.

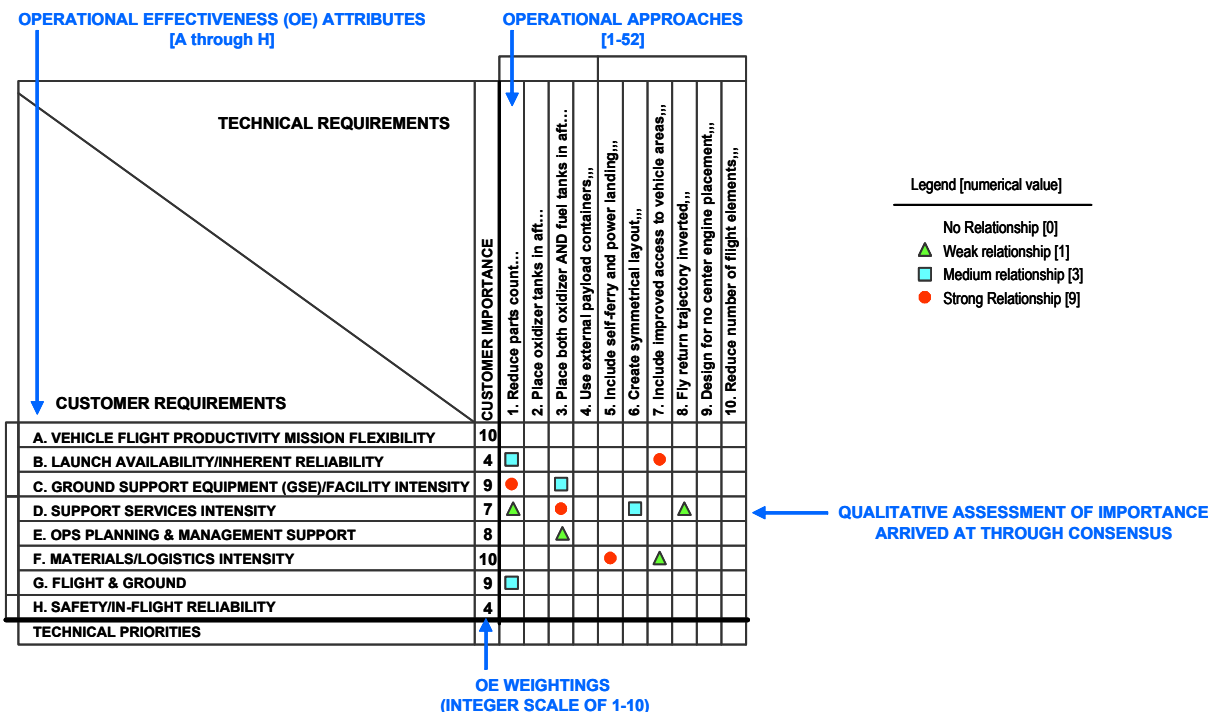
## Chapter 4 – D4Ops Approach Generation

### 4.1 INTRODUCTION

The term “D4Ops approach” refers to a process or technology which can result in a potentially better operational system. One of the major objectives of this study was to develop a set of such approaches to be applied on various Reusable Launch System (RLS) case studies (referred to as contexts). A D4Ops approach can include top level system choices about the design, such as the total number of Main Propulsion System (MPS) engines, to specific technology descriptions of various subsystems, such as the available types of Thermal Protection System (TPS) material. The D4Ops approach generation process is meant as a starting point for examination of the D4Ops philosophy. Data-mining of the Root Cause Analysis (RCS) database is a starting point in the identification of specific D4Ops approaches.

### 4.2 DEVELOPING D4OPS APPROACHES

A qualitative brainstorming discussion was initiated between SpaceWorks Engineering, Inc. (SEI), the authors, and NASA Kennedy Space Center (KSC) Systems Engineering Office. The goal was to develop a long list of potential approaches (see Appendix C). This list was narrowed down through the use of the concurrent engineering process known as Quality Function Deployment (QFD). QFD is process whereby a qualitative prioritization of products, approaches, technologies can be generated through the scoring of attributes based upon the consensus opinion of a group of experts. The rows of the QFD matrix were customer requirements, referred to as Operational Effectiveness (OE) Attributes. These were descriptions of potential wants for the system being considered. The columns of the QFD matrix represented the operational approaches developed from the RCA database and brainstorming process (narrowed down to 52 possible approaches). Each intersection of the customer requirement and operational approach was scored using a numerical value of 0, 1, 3, or 9 indicating the strength of the relationship between the parameters (see Figure 4.1). Each OE attribute was also given a weighting on an integer scale. Thus the weighting for each row was multiplied by the intersected value in the matrix (0, 1, 3, or 9), with each row subsequently being summed. Ten approaches in Top 25 showed up at least three times from all potential rankings (see Table 4.1). .



Note: Sample data is shown for the above case.

Figure 4.1. Quality Function Deployment (QFD) Overview

Table 4.1. QFD Ranking Results: 10 Approaches in Top 25 (Show up 3 Times from All Ranking Sources)

Approach Number	Approach Name
1	Reduce parts count using highly reliable parts (vs. less reliability in the parts and higher need for redundancy as in Shuttle).
10	Reduce number of flight elements (fewer flight stages)
12	Reduce tank count
16	Eliminate all hypergols in favor of LOX/LH2 propellant combination for ACS
21	Reduce engine count (use larger, fewer engines for main/OMS/RCS)
25	Eliminate need for separate OMS engines by using throttled MPS on-orbit
37	Make extensive use of high storage density batteries in place of fuel cells and APU's
41	Replace hydraulic/pneumatic systems with EMAs
45	Use common fluids AND tanks for Main Propulsion System, OMS, RCS and Power
46	Use common fluids and tanks for Main Propulsion System, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics, and ECLSS)

After examination of the QFD results, modifications were performed to the list of top approaches. These include:

- Remove approaches 10 and 12, 10 may be a very top level parameter, 12 may be included in approaches 45 and 46.
- Remove 25 since it is included in approach 21.
- This leaves 7 approaches, so add the following:
  - 17. Eliminate hypergols and cryogenic ACS propellants in favor of "green" non-cryogenic ACS propellants.

- 32. Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces.
- 35. Reduce TPS moldline penetration and repair/replacement (self-healing TPS including self-healing seals).
- 40. Incorporate Propulsion-focused IVHM.
- Fifth additional approach consists of rolling up previous approaches.

Table 4.2 lists the effort involved in conceptual level modeling of the above approaches. These are example approaches and the ability to model them is highly coupled to assumptions about the architecture being developed. The types of top level vehicle design decisions, such as main propulsion system, take-off type, outer mold line shape, etc. will affect the ability to model these operational approaches. For each operational approach, a qualitative score (1 = low, 3 = medium, 9 = high) is given in terms of modeling ability for near, mid, and far term contexts. These rankings were developed by the authors prior to knowledge about each context or modeling and simulation. Qualitative indications are that some of the approaches may be more difficult to model in near term contexts given possible constraints in integration/elimination of systems.

**Table 4.2. Representative Modeling Various New Operational Approaches**

Un-explored examples of highly synergistic sub-systems integration, whose impacts will nominally be determined through simulation include:	Ability To Model in Near Term Context (1=Easy, 3=Medium, 9=Difficult)	Ability To Model in Mid Term Context (1=Easy, 3=Medium, 9=Difficult)	Ability To Model in Far Term Context (1=Easy, 3=Medium, 9=Difficult)
1. Common tanks for OMS and RCS commodities (Shuttle has distinct, many tanks).	1	1	1
2. Common tanks for OMS, RCS and all Power commodities (such as a fuel cell or turbine unit propellant tanks).	3	3	3
3. Common fluids and tanks for Main Propulsion, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics & ECLSS).	9	9	9
4. Common / shared power, electronics, software, controllers and architecture for all engines, Guidance, Navigation and Control (GN&C) functions and Integrated Vehicle Health Management (IVHM).	9	3	3
5. Fuel Cells energy / wastes and thermal management integration (water by-products and water spray boilers).	3	3	1
Un-explored examples of highly synergistic sub-systems integration, whose impacts will nominally be determined through qualitative technology assessment include:	Ability To Model in Near Term Context (1=Easy, 3=Medium, 9=Difficult)	Ability To Model in Mid Term Context (1=Easy, 3=Medium, 9=Difficult)	Ability To Model in Far Term Context (1=Easy, 3=Medium, 9=Difficult)
6. Common, fewer, turbo-machinery, integrated into storage tanks, feeding multiple combustion processes.	3	1	1
7. Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces.	1	3	3 (rocket) / 9 (air-breather)
8. Common ground and flight power management schemes (flight systems used on checkout, no ground systems for conditioning).	9	3	1
9. Communications hardware (single elements / antennas / motors for multiple bands) and cables / interfaces and connector count.	3	1	1
10. Structural/ aerodynamics systems and safety systems (Haz Gas and Purge, Vent and Drain-PVD) as single system, lean designs resulting in reduced or eliminated fluid systems.	3	3	1
11. Increased system reliability and reduced parts / redundancy vs. less reliability / higher redundancy (as in Shuttle).	3	3	3

# Chapter 5 – Context 1

## 5.1 INTRODUCTION

In order to quantitatively assess the effect of each of the D4Ops approaches on operability, safety, and cost metrics it was necessary to develop several vehicle contexts to which the approaches could be applied. Near-, mid-, and far-term contexts were desired to explore performance and operational impacts of the D4Ops approaches on a variety of architectures. The near-term context (also called Context 1) was chosen as an Orbital Space Plane (OSP) vehicle of the type currently under consideration by NASA to fill the role of crew return and rotation to and from the International Space Station (ISS). The goal throughout the D4Ops study was to maintain focus on the enhanced operability design approaches and to avoid drawing undue attention to any particular vehicle context. In the case of the OSP context this meant examining the current design work on a wing-body OSP at NASA Johnson Space Center (JSC) and using this information to develop a similar, though not identical, vehicle architecture for use in the D4Ops research. Thus the baseline near-term context does not attempt to represent a “better” OSP design, but rather a comparable and relevant context in which D4Ops design approaches can be evaluated. Figure 5.1 illustrates the flow of the D4Ops design process for the near-term context 1 OSP.

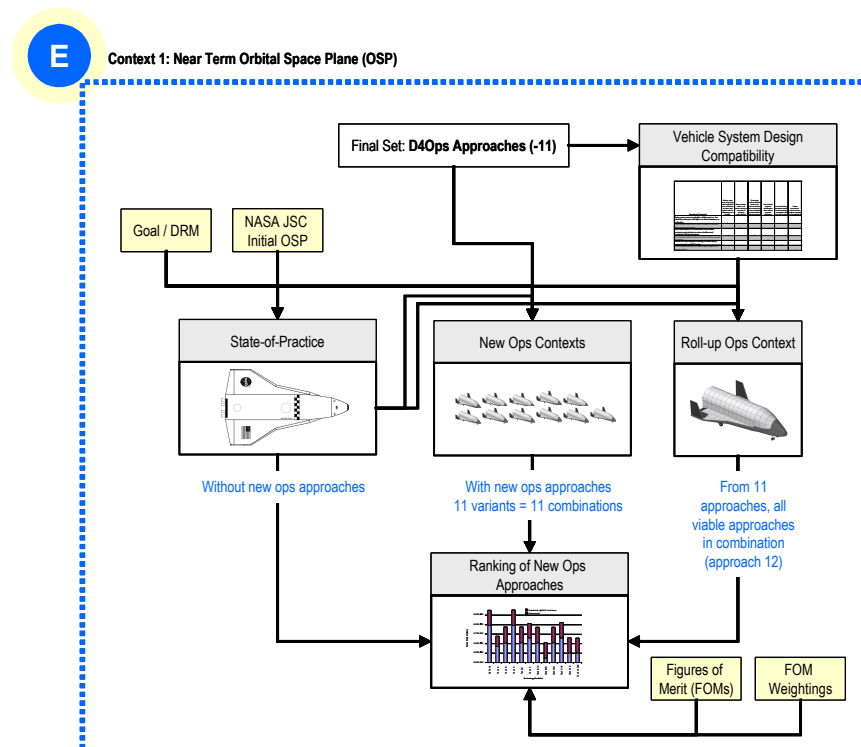
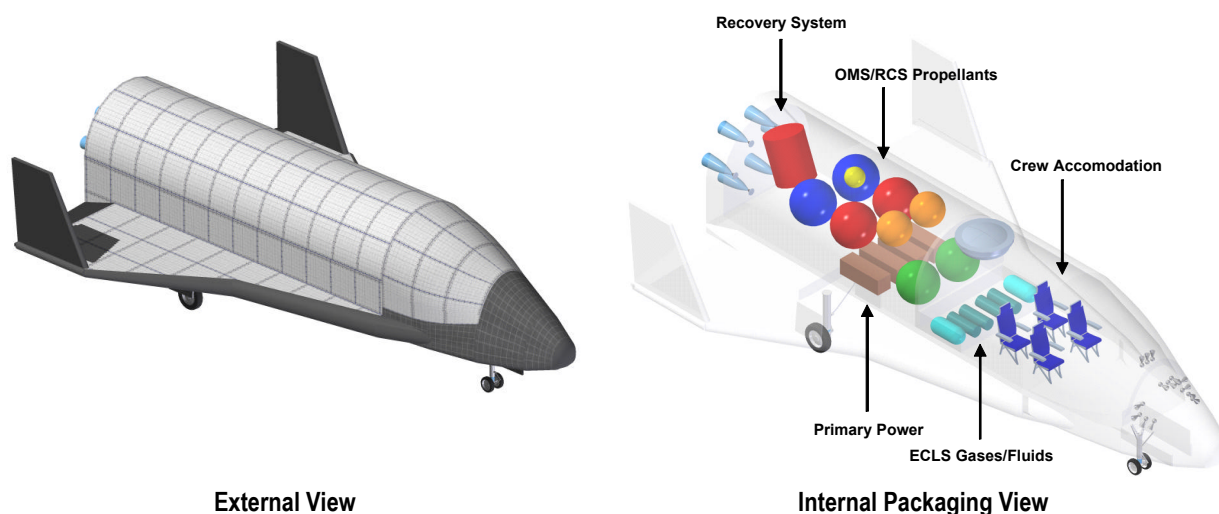


Figure 5.1. Plan for Context 1 Analysis

## 5.2 STATE-OF-PRACTICE DESIGN SUMMARY

The baseline, or state of practice (SOP), near-term Context 1 was modeled using conceptual design methods employed by the authors. The scope of the design process was limited to the OSP stage and the crew escape system (CES), and did not include the Evolved Expendable Launch Vehicle (EELV) required to boost the OSP to its initial orbit. By adhering to a very similar set of design assumptions to that used by the OSP program at NASA JSC, it was possible to produce a near-term OSP context that was comparable and relevant. Critical assumptions regarding mission parameters, configuration, propulsion, structures, thermal protection system (TPS), power generation, and

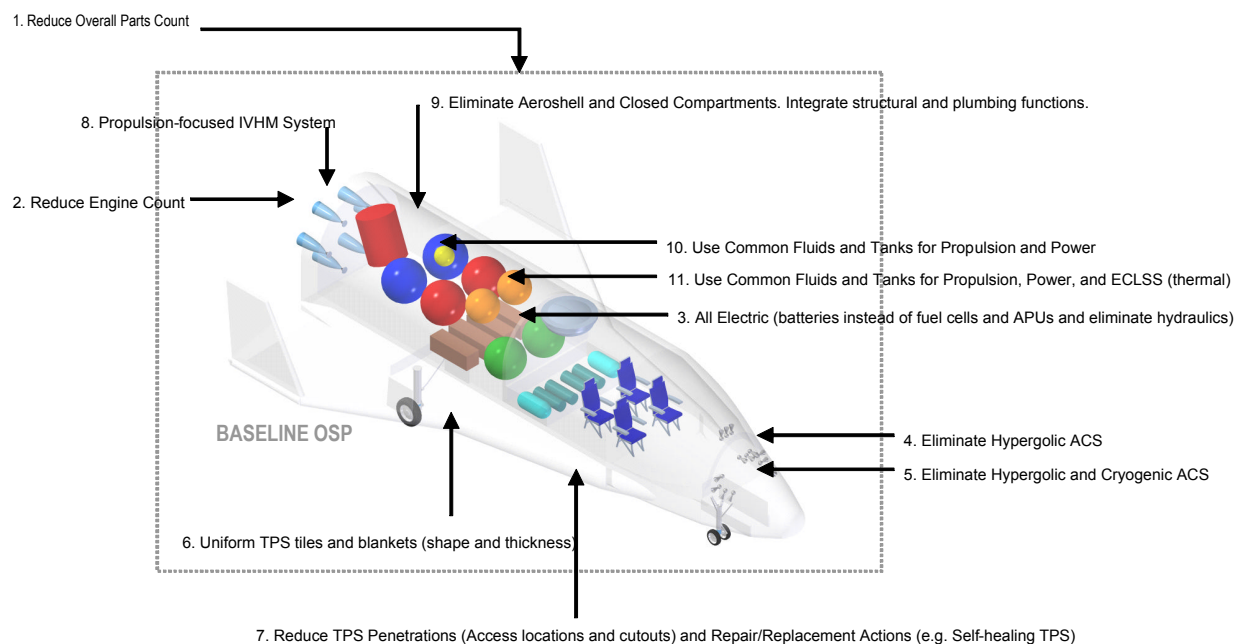
environmental control and life support (ECCLS) were similar to the JSC "winged" OSP design as of April, 2003. A summary of all applicable design assumptions made during the development of Context 1 can be found in Tables D.2 – D.4 of Appendix D. In addition, several assumptions were made when creating an operations model for the Context 1 SOP. These operations-related assumptions are listed in Tables D.5-D.8. The SOP Context 1 vehicle geometry and packaging are shown in Figure 5.2. The interior layout shows notional placement of various major subsystems including OMS propulsion, RCS propulsion, primary power, crew accommodations, ECCLS, and the recovery system. A three-view drawing of Context 1 is provided in Figure D.4. Sizing analysis for the SOP Context 1 resulted in a vehicle dry weight of 39,218 lbs, and gross weight of 55,665 lbs including the CES. A complete weight breakdown for the SOP vehicle can be found in Table D.13. Cost, safety, and operational metrics were also determined for the Context 1 SOP for later comparison with D4Ops approaches. The variable cost per flight was found to be \$32.8 M when a rate of 16 flights per year was assumed, and the total cycle time was about 55 days. A complete metrics summary is provided in Table D.13.



**Figure 5.2. D4Ops Context 1: Design Approach 0 (State-of-Practice)**

The Context 1 SOP was developed as a baseline for application of each of the eleven individual D4Ops design approaches and eventually for a roll-up design incorporating all of the D4Ops approaches that could be accommodated simultaneously. Figure 5.3 illustrates the concept of applying the various D4Ops approaches to the baseline context, while Table 5.1 details the actual design impact of each. For a more extensive explanation of how each D4Ops approach was modeled using SEI's conceptual design suite, see Tables D.9-D.12. Finally, Figure 5.4 shows a comparison of the interior packaging of the SOP Context 1 and the Approach 12 (Roll-up) Context 1.

## D4Ops approaches (No. 1-11) to be applied to baseline OSP in key functions/subsystems areas as shown



**Figure 5.3. Context 1: D4Ops Design Approaches to Be Added**

D4Ops Approach Number / Short Name	D4Ops Approach Full Name	Context 1 Implementation
0: SOP	State-Of-Practice (SOP)	Baseline
1: Reduce Parts	Reduce Overall Parts Count	Reduce tank redundancy, reduce engine redundancy, eliminate redundant fuel cells while increasing individual component reliability to maintain overall end-to-end failure rates.
2: Reduce Engines	Reduce Engine Count	Use fewer OMS and RCS thrusters (less redundancy), but increase the reliability of the thrusters to maintain current end-to-end failure rates.
3: All Electric	All Electric (batteries instead of fuel cells and APUs and eliminate hydraulics)	Use all-battery power system. Eliminate fuel cells (note APUs and hydraulic systems already eliminated in SOP baseline)
4: No Hypergols	Eliminate Hypergolic ACS	Use LOX/LH2 ACS thrusters
5: No Hypergols/Cryogens	Eliminate Hypergolic and Cryogenic ACS	Use H2O2/Ethanol thrusters
6: Uniform TPS	Uniform TPS tiles and blankets (shape and thickness)	Use uniform thickness and density TPS tiles of common shape to maximum extent practical. Thickness governed by max thickness location.
7: Robust TPS	Reduce TPS Penetrations (Access locations and cutouts) and Repair/Replacement Actions (e.g. Self-healing TPS)	Reduce TPS weight due to fewer access locations, but increase TPS acreage weights for self-healing sealant and coatings for improved damage tolerance and water resistance.
8: P-IVHM	Propulsion-focused IVHM System	Add Avionics weight for new controllers, sensors, and wiring to support P-IVHM
9: Less Aeroshell	Eliminate Aeroshell and Closed Compartments. Integrate structural and plumbing functions.	Reduce structural skin weight by using open trusswork aft of cabin on leeward side. Add additional aeroheating protection to internal tankage and components for entry protection. Combine fill and drain functions.
10: Common Prop/Power	Use Common Fluids and Tanks for Propulsion and Power	Use LOX/LH2 ACS and combined with fuel cell tanks.
11: Common Prop/Power/ECLSS	Use Common Fluids and Tanks for Propulsion, Power, and ECLSS (thermal)	Use N2 pressurant for propulsion (eliminate He) and combine with ECLSS; use LOX/LH2 ACS and combine with fuel cells. (Note ECLSS water tanks already integrated with fuel cells in SOP baseline).
12: Roll-Up	All Applicable D4Ops Approaches (for OSP context use: 1-4, 6-9, 11). Assume 4 and 11 preclude approach 5. Also assume that approach 11 supercedes approach 10.	Reduce tank redundancy and tank counts, use common LOX/LH2 fluids for propulsion and ECLSS (for O2). Use N2 for ECLSS and pressurization. Reduce OMS engines and thrusters. Use all batteries rather than fuel cells. Improve TPS robustness/maintenance and eliminate TPS penetrations as practical. Use uniform thickness TPS tiles of common size where practical. Add propulsion-focused IVHM. Eliminate leeward skin panel structures aft of crew cabin to eliminate closed spaces. Combine plumbing fill/drain functions. Combine tankage between propulsion and ECLSS.

**Table 5.1. Context 1: D4Ops Design Approaches to Be Added**

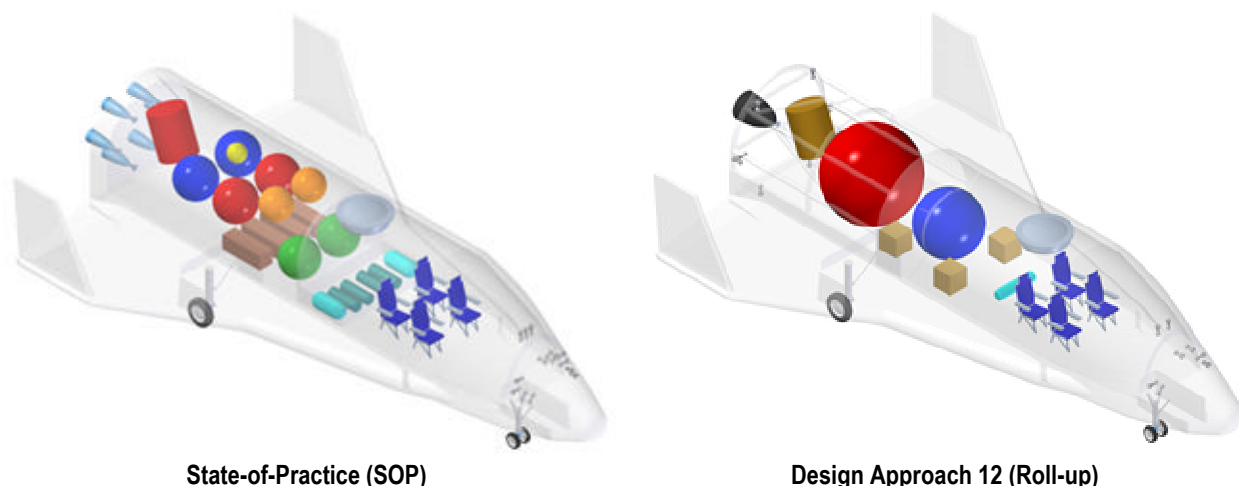


Figure 5.4. D4Ops Context 1: Design Approach Comparison-SOP versus Approach 12 (Roll-up)

### 5.3 CONTEXT 1 ANALYSIS OF D4OPS DESIGN APPROACHES

A variety of performance, cost, safety, and operability metrics were determined for each of the twelve vehicle contexts resulting from the application of D4Ops approaches to the baseline Context 1. This data was required in order to fulfill one of the principle goals of the study: to quantify the impact, in a relevant context, of each D4Ops design approach on a set of metrics. In order to create a ranking of the D4Ops approaches based on their benefits in the context of a near-term OSP, a series of weighting scenarios were examined using the TOPSIS method (see Figure D.18). Examples of these scenarios include even weighting of all metrics, non-recurring cost centric, weight centric, cycle time and safety centric, and others. Table D.18 outlines each of the weighting scenarios and lists the applied weights. A rank is assigned to each approach for each weighting scenario as seen in Table D.19. Finally, a median rank is calculated across all weighting scenarios in an attempt to identify the best design approach. Figure 5.5 below showcases the final median rankings of the D4Ops design approaches for Context 1, and also illustrates the results of four of the weighting scenarios.

The analysis results for the twelve approaches contain a wealth of useful information beyond the final rankings themselves. A direct comparison of the raw metrics data for the family of approaches is shown in Tables D.14 and D.15. Normalized metrics data from each approach is compared in Tables D.16 and D.17. One can see from these tables, for instance, that Approach 1 (Reduce Parts) resulted in the lowest dry weight, Approach 3 (All Electric) gave the lowest DDT&E cost, and Approach 12 (Roll-up) offers the shortest total cycle time. Figures D.12-D.14 display a comparison of the weight, non-recurring cost, and operations metrics for each approach to baseline metrics (as a percentage difference). The weight penalty associated with Approach 12 (Roll-up) is clearly seen in Figure D.12, while Figure D.14 shows the drastic improvement in the operations metric that this same approach achieves. Figure D.15 shows life cycle cost per flight for each of the D4Ops approaches. The accumulation of initial program costs for the SOP Context 1 is shown in Figure D.16. Figure D.17 demonstrates how the cumulative life cycle cost for each of the design approaches compares with the SOP Context 1.

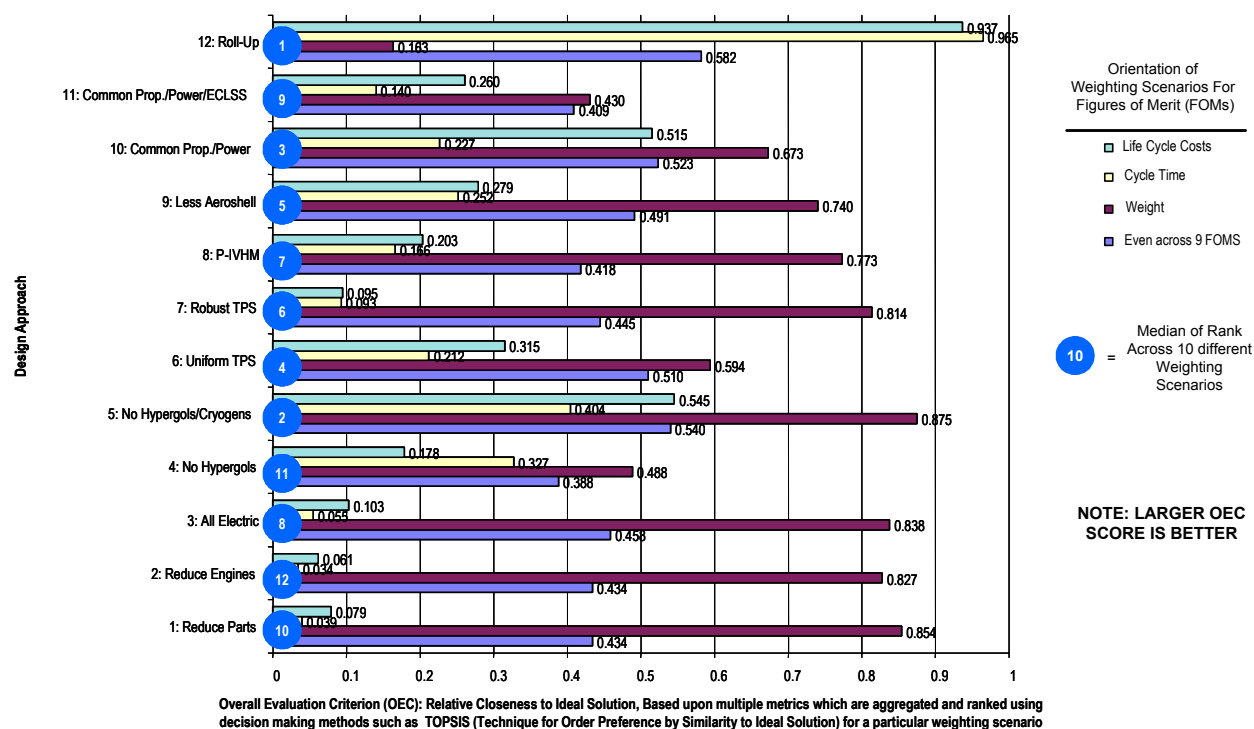


Figure 5.5. D4Ops Context 1: TOPSIS Ranking of Design Approaches

## 5.4 CONTEXT 1 SUMMARY AND CONCLUSIONS

In summary, a baseline near-term OSP context was developed similar to a crew transport vehicle under study by NASA JSC. From this baseline, a series of D4Ops approaches were applied individually and then simultaneously, and the impacts on a set of metrics were recorded for each. A ranking of the approaches was produced using this collection of data and a set of weighting scenarios.

It was possible to draw a number of conclusions from the analysis of the D4Ops design approaches in Context 1. First of all, as Figure 5.5 shows Approaches 12, 5, and 10 placed first, second, and third respectively when the median ranking across weighting scenarios was performed. The success of Approach 12 (Roll-up) in the final ranking indicates that the advantages of enhanced operability design approaches can outweigh their real or perceived penalties. For instance, Figure D.17 demonstrates how Approach 12 can, in spite of its high initial cost, achieve a cumulative life cycle cost much lower than the baseline due to reduced operational costs. The common threads among the three top ranked approaches seem to be integrating tankage among subsystems, and using safer, more benign fluids for propulsion and power. Just reducing parts count or the number of engines may be necessary but not sufficient for producing the best overall design. Also, it appears that employing selectively uniform TPS has the potential to significantly improve the operability of a design.

Upon completing the OSP context analysis, it was concluded that examining only one element of a broader architecture, as opposed to an end-to-end system, likely limited the improvements attained by incorporating D4Ops approaches. The results of the analysis on Context 2 support this conclusion. While it can be seen from the analysis that the D4Ops approaches add weight penalties to the OSP Context, possibly as high as 10%, it is encouraging that the resulting weight delta was only the amounts indicated in each case. This relatively small negative affect on weight was in exchange for significantly improved operations metrics. This points the direction for future design, analysis and experimental vehicles emphasizing a need to reduce parts count, such as by improved reliability at component, system and sub-system levels, such as to allow reduced redundancy (weight) at equal or improved levels of safety as compared to current approaches. On the opposing variable of DDT&E and TFU costs, it can be concluded that similar to D4Ops approaches, future work must address the ability to create systems designs, not just

technology, in novel ways and also to manufacture these systems. Future work into new development and manufacturing systems and organizations for the creation of low volume, but complex, and reliable systems is urgently needed.

## Chapter 6 – Context 2

### 6.1 INTRODUCTION

The second context in which the D4Ops design approaches were evaluated was a mid-term RLS architecture. For the purposes of this study “mid-term” was considered to mean a vehicle whose initial operating capability (IOC) occurred around 2015. In the interest of establishing a comparable and relevant context, the study authors reviewed the design work conducted by NASA as part of the Next Generation Launch Technologies (NGLT) program on a mid-term, Two-Stage-To-Orbit (TSTO) architecture. This vehicle concept was identified as NGLT Architecture 5 at the time the study was conducted. Using the NGLT Architecture 5 concept as an example, a similar, but not identical, TSTO vehicle was developed by SEI to serve as a mid-term context. Unlike the near-term Context 1, Context 2 was a complete end-to-end system that required iterative vehicle performance closure to analyze each design approach. Figure 6.1 below describes the D4Ops process as it was implemented for the mid-term Context 2 TSTO.

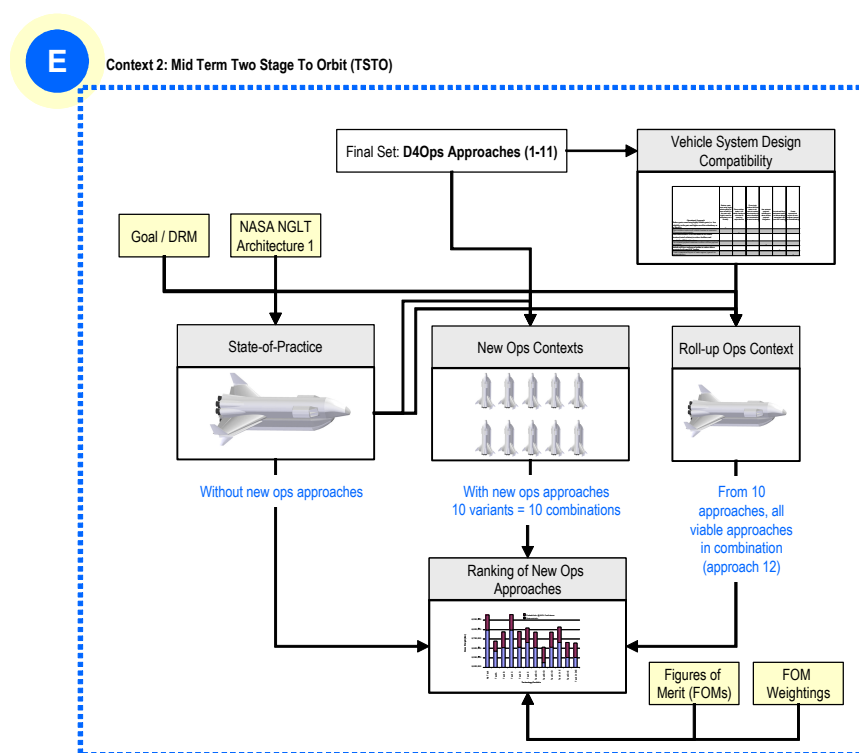


Figure 6.1. Plan for Context 1 Analysis

### 6.2 STATE-OF-PRACTICE DESIGN SUMMARY

The baseline mid-term Context 2 was modeled using an expanded set of conceptual design tools beyond those required for Context 1. Since the scope of the design process encompassed an entire Earth-To-Orbit (ETO) launch system, a vehicle closure process involving trajectory simulation and weights and sizing was required to quantify the impact of an approach. Operating under a similar set of design assumptions to that used by the NASA NGLT Architecture 5, the authors were able to develop a mid-term TSTO baseline that exhibited comparable performance. Critical assumptions regarding mission parameters, configuration, propulsion, structures, thermal protection system (TPS), and primary power were similar to the Architecture 5 design as of October, 2003. A summary of all applicable design assumptions made during the development of Context 2 can be found in Table E.1 of Appendix E.

The SOP Context 2 booster stage geometry and packaging is shown in Figure 6.2. Similarly, the geometry and packaging of the SOP orbiter stage is illustrated in Figure 6.3. The interior layout shows notional placement of various major subsystems including OMS propulsion (orbiter stage only), RCS propulsion, primary power, avionics, and thermal control. Three-view drawings of the Context 2 booster and orbiter are provided in Figures E.4 and E.5. Sizing analysis for the SOP Context 2 resulted in a booster dry weight of 472,856 lbs, an orbiter dry weight of 184,737 lbs, and a total system gross weight of 4,290,683 lbs. A complete weight breakdown for the SOP vehicle can be found in Table E.5. Cost, safety, and operational metrics for the Context 2 SOP were recorded for later comparison with D4Ops approaches. The operations cost per flight was found to be \$386.5 M when a rate of 5 flights per year was assumed, and the total turnaround time was about 79 days. A complete metrics summary is provided in Tables E.5-E.7. The Context 2 SOP was developed as a baseline for application of each of the eleven individual D4Ops design approaches and for a roll-up design incorporating all of the D4Ops approaches that could be accommodated simultaneously. Figures 6.4 and 6.5 illustrate the concept of applying the various D4Ops approaches to the baseline context, while Table 6.1 details the actual design impact of each. For a more extensive explanation of how each D4Ops approach was modeled using SEI's conceptual design tools, see Tables E.2-E.4.

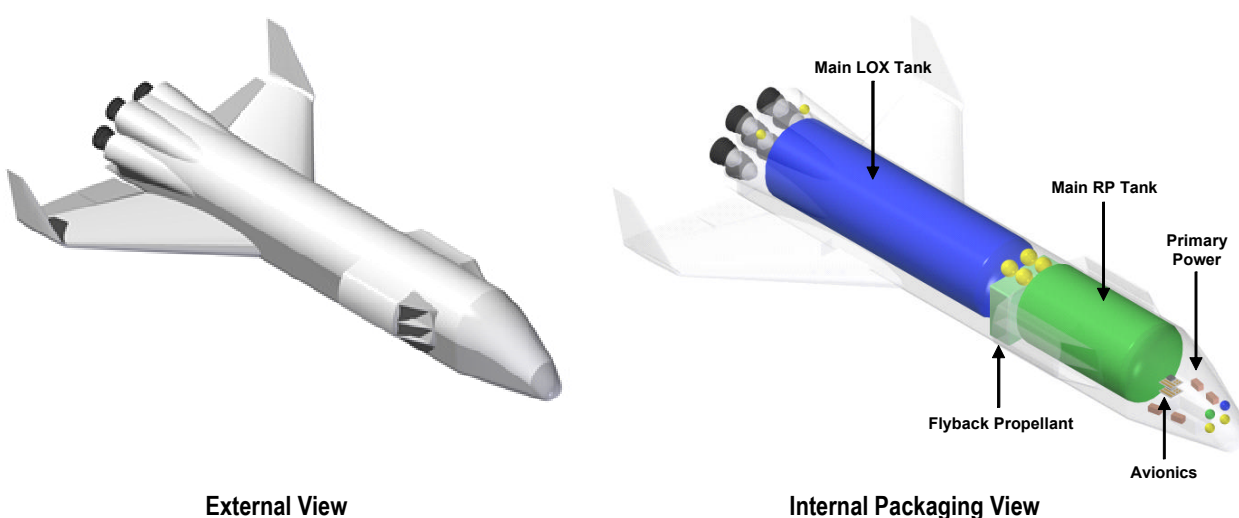


Figure 6.2. Mid-term Context 2 Booster Geometry and Packaging

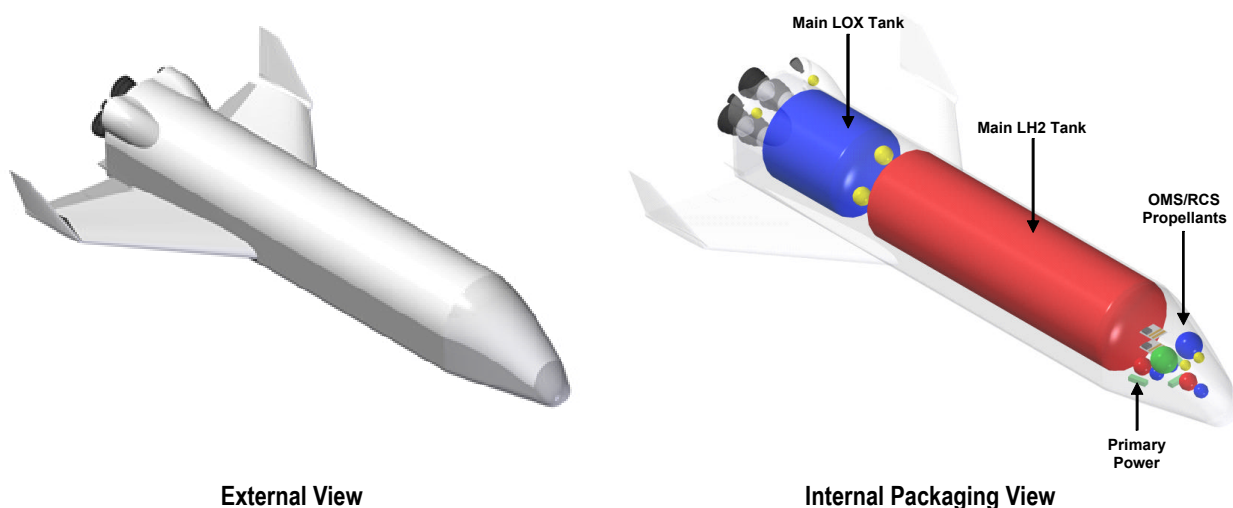
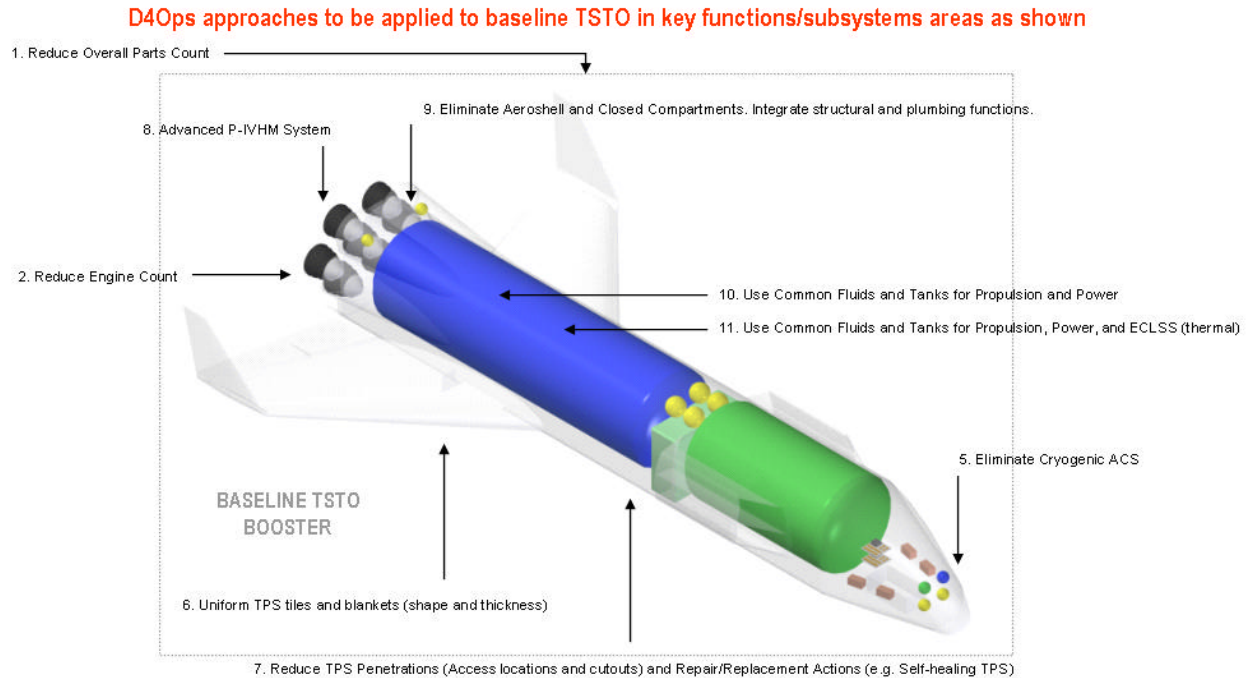
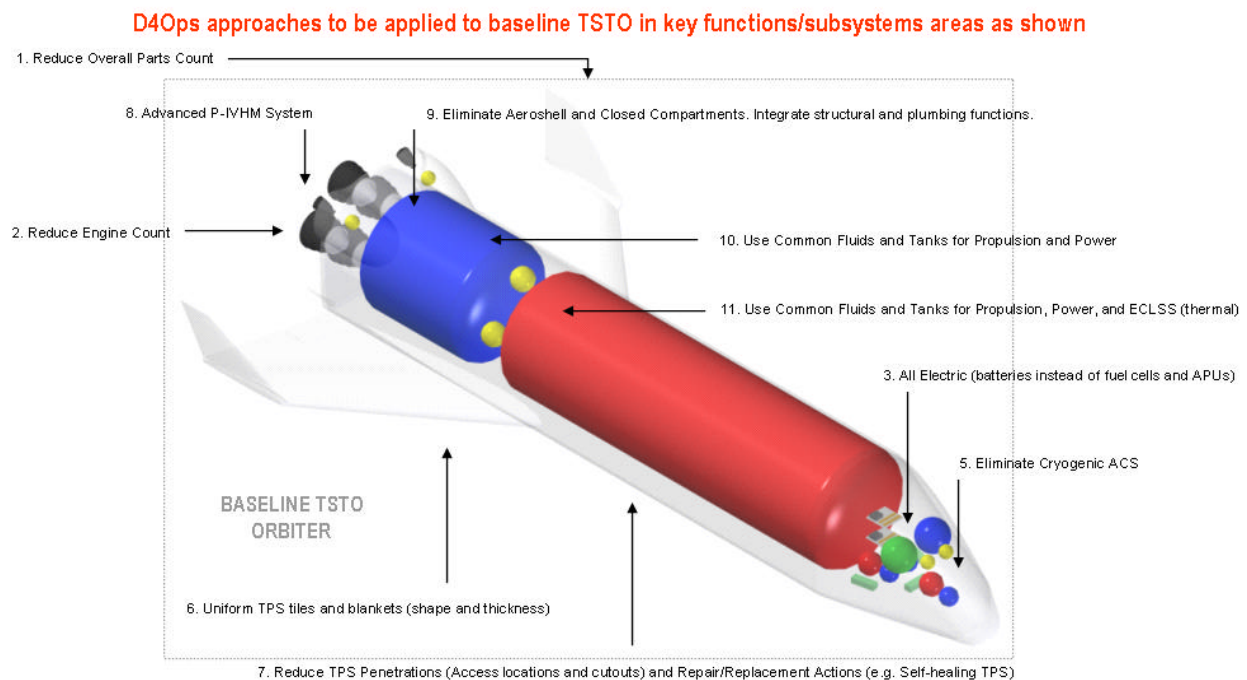


Figure 6.3. Mid-term Context 2 Orbiter Geometry and Packaging



**Figure 6.4. Context 2 Booster: D4Ops Design Approaches to Be Added**



**Figure 6.5. Context 2 Orbiter: D4Ops Design Approaches to Be Added**

**Table 6.1. Context 2: D4Ops Design Approaches to be Added**

D4Ops Approach Number / Short Name	D4Ops Approach Full Name	Context 2 Implementation
0: SOP	State-Of-Practice (SOP)	Baseline
1: Reduce Parts	Reduce Overall Parts Count	Reduce tank redundancy, reduce engine redundancy, eliminate redundant fuel cells, eliminate redundant avionics while increasing individual component reliability to maintain overall end-to-end failure rates.
2: Reduce Engines	Reduce Engine Count	Reduce main engine count on both stages. Use fewer OMS and RCS thrusters (less redundancy), but increase the reliability of the thrusters to maintain current end-to-end failure rates.
3: All Electric	All Electric (batteries instead of fuel cells and APUs and eliminate hydraulics)	Use all-battery power system. Eliminate fuel cells (note hydraulic systems already eliminated in SOP baseline)
4: No Hypergols	Eliminate Hypergolic ACS	Not applicable. Hypergols already eliminated on SOP vehicle.
5: No Hypergols/Cryogens	Eliminate Hypergolic and Cryogenic ACS	Use H2O2/Ethanol thrusters
6: Uniform TPS	Uniform TPS tiles and blankets (shape and thickness) in selected areas. Left / Right mirroring of TPS.	Selectively use uniform thickness and density TPS tiles of common shape to maximum extent practical. Thickness governed by max thickness location.
7: Robust TPS	Reduce TPS Penetrations (Access locations and cutouts) and Repair/Replacement Actions	Reduce TPS weight due to fewer access locations, but increase TPS acreage weights for sealant and coatings for improved damage tolerance and water resistance.
8: P-IVHM	Advanced IVHM System	Add Avionics weight for new controllers, sensors, and wiring to support IVHM
9: Less Aeroshell	Eliminate Aeroshell and Closed Compartments. Integrate structural and plumbing functions.	Reduce structural skin weight by using open trusswork on aft end (base structure). Add additional aeroheating protection to internal tankage and components for entry protection. Repackage propellant tanks to shorten interstage aeroshell. Combine fill and drain functions.
10: Common Prop./Power	Use Common Fluids and Tanks for Propulsion and Power	Upgrade fuel-cells to utilize propellant grade LOX and LH2. Eliminate fuel cell reactant tanks and draw from main propellant tanks. Switch OMS/RCS to cryogenic LOX/LH2 (orbiter). Eliminate OMS and RCS tanks (orbiter). Add catch screens to main tanks for subsystems, OMS propellants, and RCS propellants. Eliminate Helium and pressurant tanks. Switch to electric boost pumps powered by fuel cells for OMS/RCS engines.
11: Common Prop./Power/ECLSS	Use Common Fluids and Tanks for Propulsion, Power, and ECS (thermal)	Upgrade fuel-cells to utilize propellant grade LOX and LH2. Eliminate fuel cell reactant tanks and draw from main propellant tanks. Switch OMS/RCS to cryogenic LOX/LH2. Eliminate OMS and RCS tanks. Add catch screens to main tanks for subsystems, OMS propellants, and RCS propellants. Eliminate Helium and pressurant tanks. Switch to electric boost pumps powered by fuel cells for OMS/RCS engines. Remove Freon but maintain water tank for electronics cooling.
12: Roll-Up	All Applicable D4Ops Approaches (for TSTO context use: 1-3, 6-9, 11). Assume approach 4 precludes approach 5. Also assume that approach 11 supercedes approach 10.	Reduce main engine count. Eliminate OMS engines and use deeply-throttled single MPS engine. Reduce redundancy in avionics (from double to single). Replace fuel cells with Li-Ion batteries (400 W-hr/kg). Eliminate all tankage and reactants for fuel cells. Remove Freon (R-21) but maintain water tank for electronics cooling. Replace TUFFI tiles with uniform thickness tiles in selected areas along leading edges of wings, windward surfaces, and nose. Increase selective FRSI blanket thicknesses for uniform thickness. Reduce redundancy in RCS thruster count. RCS will maintain same total thrust and delta-V capability. RCS and OMS propellants to be provided by main tanks (orbiter). Thus, eliminate all RCS and OMS tankage and add catch screens to tanks for OMS and RCS propellants. Eliminate Helium and pressurant tanks. Add electric boost pumps powered by Li-Ion batteries. Reduce vehicle access points in nose section, intertank, and aft sections. Add VHM sensors to vehicle body structure, wings, ACS engines, and tanks. Add additional processors and controller hardware to avionics banks. Repackage propellant tanks to shorten interstage aeroshell. Eliminate base shield. Add thermal blankets and insulation to aft RCS/OMS tanks, feed lines, and exposed subsystems.

### 6.3 CONTEXT 2 ANALYSIS OF D4OPS DESIGN APPROACHES

A set of metrics was determined for each of the twelve vehicle contexts resulting from the application of D4Ops approaches to the baseline Context 2. With this data in hand it was possible to quantify the impact, in a relevant context, of each D4Ops design approach on the desired metrics. In order to create a ranking of the D4Ops approaches based on their benefits in the context of a mid-term TSTO, a series of weighting scenarios were examined using the TOPSIS method as with Context 1. Table E.12 outlines each of the weighting scenarios and lists the applied weights. The rank assigned to each approach for each weighting scenario can be seen in Table E.13. A median rank across all weighting scenarios was calculated in the same manner as in Context 1. Figure 6.7 below showcases the final median rankings of the D4Ops design approaches for Context 2, and also illustrates the results of four of the weighting scenarios.

The analysis results for the twelve Context 2 approaches encapsulate a large amount of information from which observations can be made. A direct comparison of the raw metrics data for the family of approaches is shown in Tables E.8 and E.9. Normalized metrics data from each approach is compared in Tables E.10 and E.11. From these figures one can see that Approach 9 (Less Aeroshell) resulted in the lowest dry weight, Approach 3 (All Electric) gave the lowest DDT&E cost, and Approach 12 (Roll-up) offers the shortest total cycle time. Figures E.12 - E.14 show a comparison of the weight, non-recurring cost, and operations metrics of each approach to the baseline metrics as a percent difference. Although Approach 12 attained the best overall cycle time, its poor performance in terms of both weight (see Figure E.12) and non-recurring cost (see Figure E.13) led to a low final ranking. The

accumulation of initial program costs for the SOP Context 2 is shown in Figure E.15. Figure E.16 demonstrates how the cumulative life cycle cost for each of the design approaches compares with the SOP Context 2.

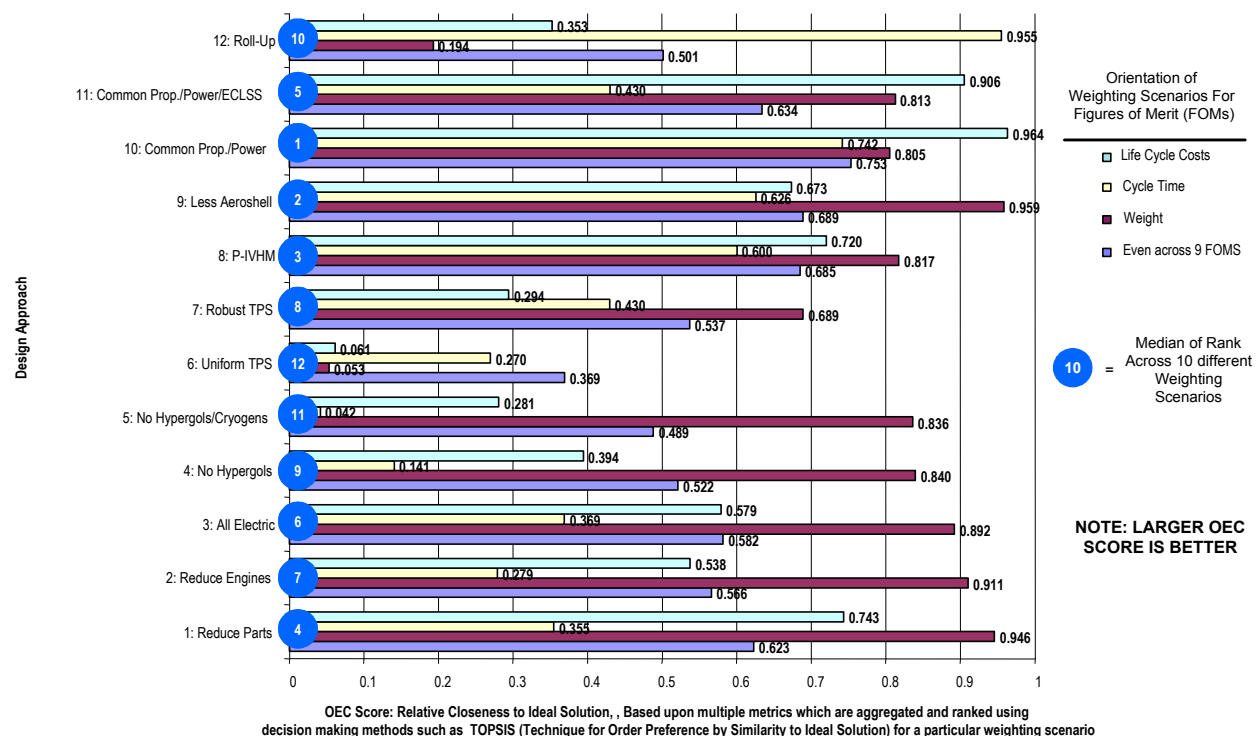


Figure 6.7. D4Ops Context 2: TOPSIS Ranking of Design Approaches

## 6.4 CONTEXT 2 SUMMARY AND CONCLUSIONS

In summary, a baseline mid-term TSTO context similar to architectures under study by NASA was developed. From this baseline, a series of D4Ops approaches were applied individually and then simultaneously, and the impacts on a set of metrics were recorded for each. A ranking of the approaches was produced based on the collected data and a set of weighting scenarios.

As Figure 6.7 shows Approaches 10, 9, and 8 placed first, second, and third respectively when the median ranking across weighting scenarios was performed. It is interesting to note that Approach 10 (Common Fluids/Tanks for Propulsion/Power) appears among the top three approaches for both the near-term Context 1 and mid-term Context 2. Approach 9 (Less Aeroshell) was more influential when applied to Context 2 than Context 1 because in the case of Context 2, the iterative vehicle closure process allows the weight reduction to propagate through both stages of the vehicle. For instance, reducing aeroshell on the orbiter stage has the effect of reducing the weight on both the booster and orbiter when the vehicle is re-closed. Approach 8 (P-IVHM) ranks third in the median rankings due to the fact that it provides moderate operational benefits with a small weight penalty. Unlike the near-term Context 1, the commonalities between the top ranking approaches are less obvious in Context 2. From Table E.13 it is apparent that Approaches 10, 9, and 8 occupy the top three spots in both the safety focused weighting scenario and the DDT&E and GSE focused scenario. These observations suggest that design approaches that tend to reduce exposure to hazardous fluids or closed compartments have the greatest effect on improving operational metrics for an end to end system.

## Chapter 7 – Context 3

### 7.1 INTRODUCTION

The final contexts in which a set of D4Ops design approaches were evaluated were a pair of advanced, far-term architectures. For the purposes of this study “far-term” was taken to mean a vehicle whose IOC was around 2020. Discussion between study participants, the authors and personnel at NASA KSC, led to changes in the implementation of the D4Ops process for Contexts 3a and 3b. First of all, unlike Contexts 1 and 2, 3a and 3b would not be based on any particular existing design study. Secondly, instead of developing a baseline Context and then applying D4Ops design approaches one by one as done previously, Contexts 3a and 3b would incorporate D4Ops thinking from the beginning. It was decided that modifications to the initial list of eleven D4Ops design approaches should be made before proceeding to the far-term context analysis. The authors reviewed the list of ideas conceived during the initial D4Ops brainstorming session (see Appendix C), and reviewed operational design recommendations published by the Space Propulsion Synergy Team (SPST). Several new D4Ops approaches were subsequently added to the original eleven, while some of the existing approaches were combined. The resulting list of design approaches is contained in Table 7.1. Figure 7.1 outlines the Context 3 D4Ops design process.

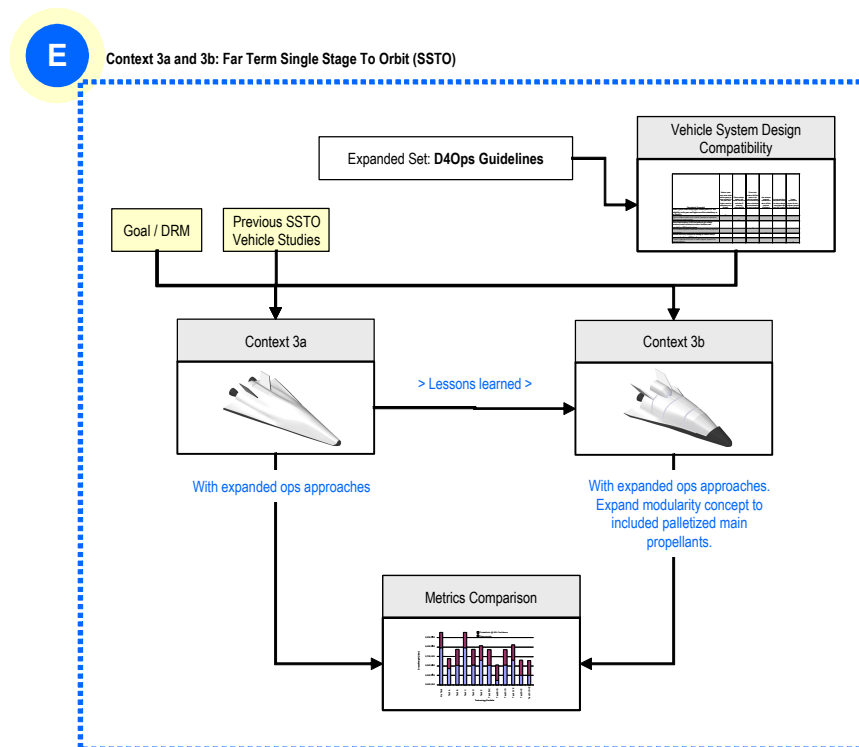


Figure 7.1. D4Ops Context 3 Plan

Table 7.1. Expanded List of D4Ops Design Approaches

	Design Guideline	Description
CONFIGURATION	Incorporate Modular Design Approach	Locate propellant tankage and subsystems on pallet modules
	Fly Return Trajectory Inverted	Minimize windward TPS penetrations by re-entering atmosphere inverted
	Place LOX Tank Aft	If applicable, position LOX tank in aft end of fuselage in order to shorten or eliminate feedlines
PROPULSION	Utilize MPS with Improved Design Life	Main propulsion system should have improved design life compared with SSME in terms of duration and number of starts
	Reduce Main Engine Count	Reduce system complexity by reducing number of main engines (while increasing individual engine reliability)
	Reduce Likelihood of Gas / Liquid Leakage	Design connector and distribution systems to minimize risk of gas or liquid propellant leakage
	Design Accessible Propulsion System	Propulsion system components should be arranged to facilitate support and maintenance
	Avoid Using Center Engine	Avoid multi-engine designs in which a main engine is positioned in the center of a group of engines (poor access for engine maintenance)
	Reduce RCS Thruster Count	Reduce system complexity by employing fewer RCS thrusters than STS baseline (while simultaneously increasing the reliability of individual units)
	Use Non-toxic / Benign Propellants for OMS / RCS	Avoid chemicals such as hydrazine, MMH, and NTO to improve supportability and maintainability
STRUCTURES	Use Left / Right Symmetric TPS	Design mirrored TPS such that left and right TPS layouts are symmetric for a large percentage of the surface area
	Use Selectively-Uniform TPS Layout	Increase maintainability and supportability of TPS by using uniform (common shape/thickness) tiles or blankets on selected surfaces
	Reduce TPS Penetration Points	Design for minimal TPS penetration locations on vehicle. Use robust TPS design where penetrations are required
	Eliminate Closed Compartments	Remove aeroshell in selected areas to eliminate closed compartments and improve maintainability and supportability
MECHANICAL	Eliminate Hydraulic Systems	Use EMA / EHA systems for landing gear, aerosurface actuation, ect.
	Reduce / Eliminate Fuel Cells	Use high energy density storage batteries where possible in place of fuel cells to reduce complexity
	Incorporate P-IVHM	Include propulsion-focused IVHM system to improve ground checkout, safety, and maintainability
INTEGRATION	Use Common Fluids for Propulsion, Power, and Thermal Management	Design systems, tankage, and feedlines such that common fluids can be used for propulsion, power, and thermal management functions. Reduce number of unique fluids on vehicle to improve maintainability and supportability
	Integrate OMS / RCS Tankage and Hardware	Where possible, combine propellant tankage and hardware for OMS and RCS to improve supportability and maintainability
INTERFACES	Reduce Flight to Ground Interfaces	Design systems such that number of flight to ground interfaces is reduced compared with STS baseline

## 7.2 CONTEXT 3 DESIGN SUMMARY

### 7.2.1 CONTEXT 3A DESIGN SUMMARY

A variety of far-term architectures were considered before selecting the configuration seen in Context 3a. Major attributes such as number of stages, type of propulsion, take-off orientation, landing orientation, propellants, and mission were discussed. The array of options was qualitatively evaluated based on D4Ops design principles and lessons learned from Contexts 1 and 2. The outcome for Context 3a was a fully reusable, all-rocket SSTD that takes off vertically and lands horizontally (see Figure 7.2). The design includes a high degree of TPS shape commonality, all-electric actuation, and the notion that the aft face of the vehicle is not covered by an aeroshell. The Main Propulsion System (MPS) is easily accessible, and is designed to operate at 90% of its design power level during ascent to increase design life. These main engines will also be deeply throttled for use in orbital maneuvering. Figure 7.3 identifies the D4Ops approaches incorporated in Context 3a. A three-view drawing of Context 3a can be found in Figure F.4 Appendix F. A scale comparison of Context 3a, 3b, and the Space Shuttle stack is shown in Figure F.6.

The reference mission was based loosely on the DARPA Operational Responsive Spacelift (ORS) Force Application and Launch from CONUS (FALCON) requirements. From the DARPA specifications a payload of 12,000 lbs to a 100 nmi. circular orbit at 28.5 degrees was chosen for Context 3. Tables F.1 and F.2 list all of the design assumptions for both of the Context 3 vehicles. The vehicle performance closure for Context 3a and 3b was slightly different from that of Context 2. The primary difference was that Context 3a and 3b were simulated with variable mixture ratio throughout the ascent phase to improve gross weight values. Figures F.1 and F.2 describe the Context 3 design process.

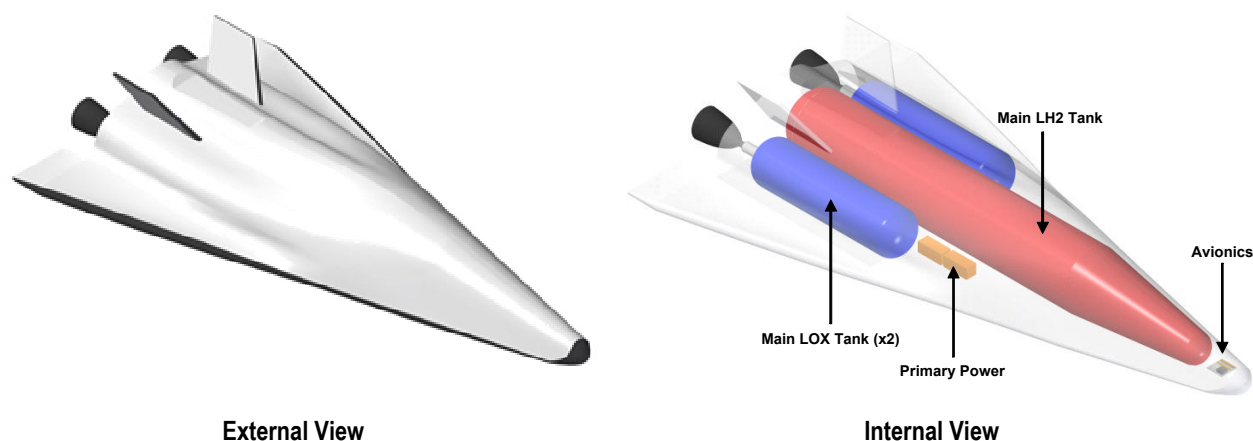
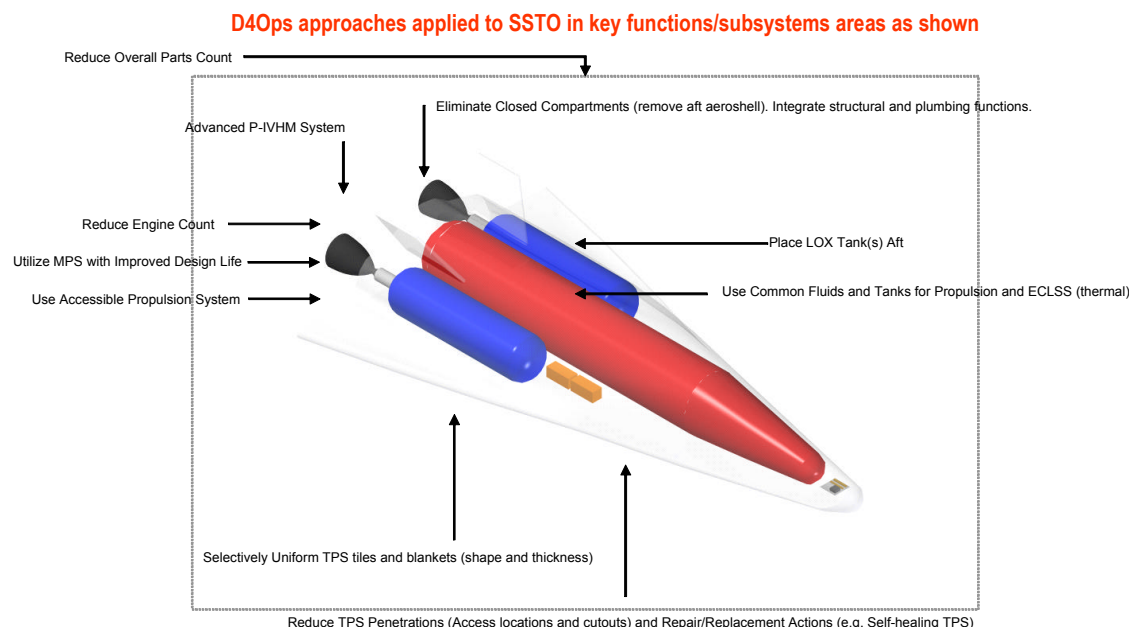


Figure 7.2. D4Ops Context 3a Geometry and Packaging



**Figure 7.3. D4Ops Design Approaches Included in Context 3a**

## 7.2.2 CONTEXT 3B DESIGN SUMMARY

The original intention had been to develop and analyze a single Context 3 vehicle using D4Ops approaches from the beginning of the design. However, after completing work on the first far-term vehicle, Context 3a, several interesting design approaches listed in Table 7.1 still had not been fully investigated. In particular, the idea of modular design had not previously been implemented and its benefits and costs were not known. There was also a desire to see a more extreme implementation of the reduced aeroshell approach since this strategy had produced favorable results on the other contexts. Context 3b was developed in response to these unanswered questions.

Brainstorming for Context 3b resulted in several design architecture ideas. First, the use of modular pallets to carry the main propellants was discussed. Conceptually these pallets would resemble the Extended Duration Orbiter (EDO) pallets used occasionally on the Space Shuttle. Preliminary examination of the packaging of such pallets in a far-term single stage vehicle proved that such an idea was not feasible. Another initial Context 3b design called for a fuselage whose upper surface (aeroshell structure) could be detached and lifted off during maintenance. Doing so would enable technicians to perform maintenance and inspections without the need to purge closed fuselage compartments. However, this concept was also set aside because it was perceived as only a small departure from the Context 3a vehicle.

The configuration that was eventually agreed upon is shown in Figure 7.4 below. This design showcases both the modularity and reduced aeroshell approaches. The main fuel and oxidizer are stored in conformal tanks that are assumed to be removable during normal ground operations. Since the fuselage has only limited aeroshell structure to protect the tanks, their exposed surfaces are covered by TPS blankets. The tight packaging of the propellant tankage allowed Context 3b to be considerably smaller and lighter than Context 3a while still performing the same mission (12,000 lbs to LEO). Figure 7.5 shows the particular D4Ops design approaches that were studied in Context 3b. A three-view drawing of Context 3b can be found in Figure F.5.

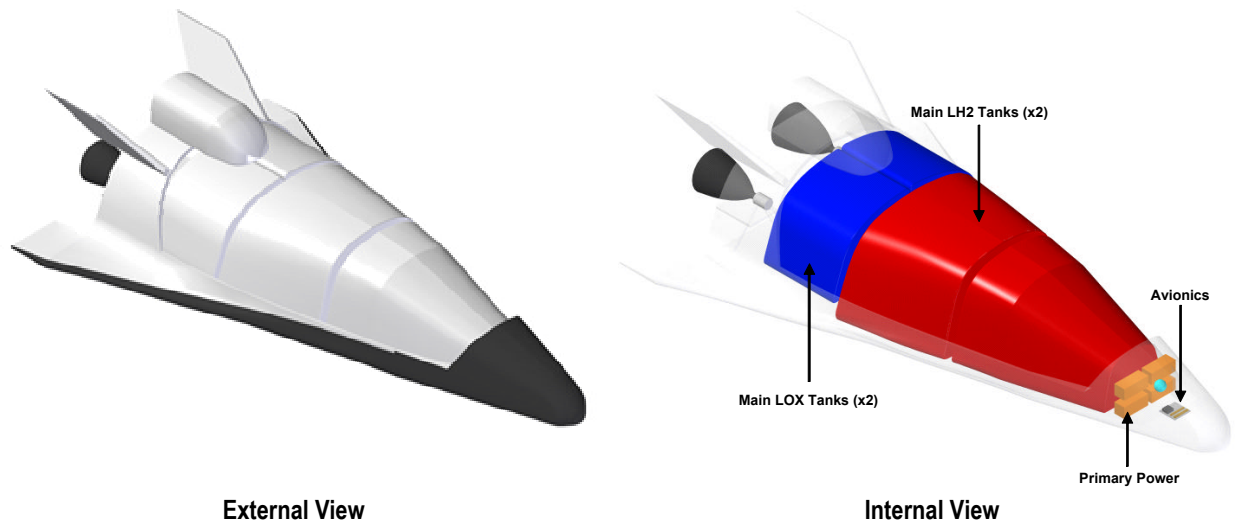


Figure 7.4. D4Ops Context 3b Geometry and Packaging

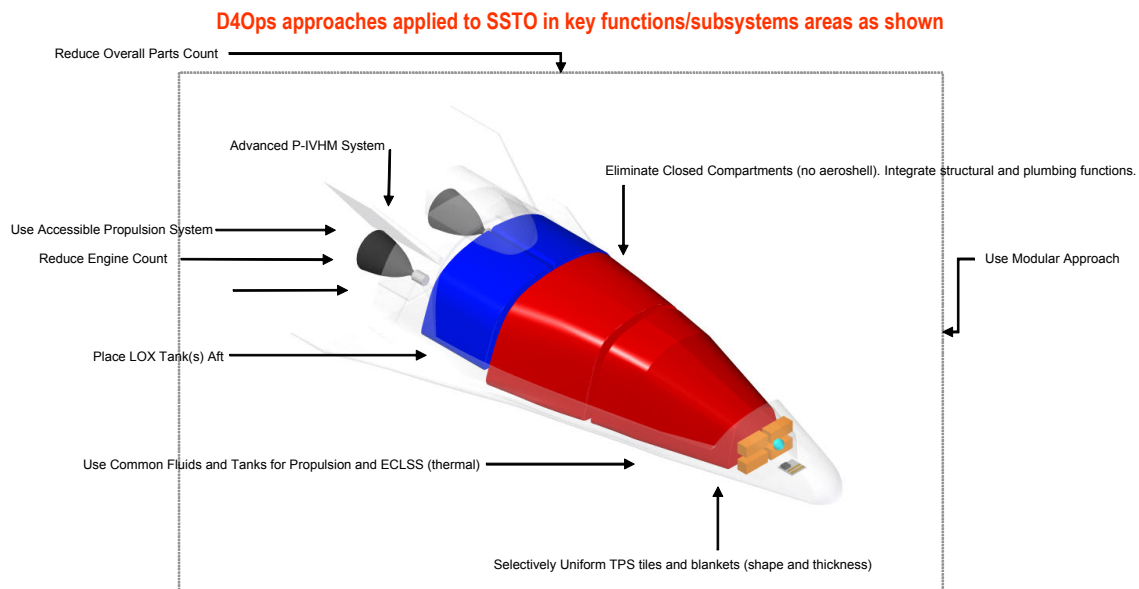


Figure 7.5. D4Ops Design Approaches Included in Context 3b

## 7.4 CONTEXT 3 SUMMARY AND CONCLUSIONS

The objective of Context 3 was to attempt to use D4Ops principles from the outset of a new, far-term vehicle design. The hope was that by applying the conclusions and lessons learned from Contexts 1 and 2 the authors would be able to act on the idea of designing for operations. The experience gained in the course of the conceptual design process resulted in several important conclusions. First and foremost, the fact that old habits are hard to break was made evident early on in the Context 3 analysis. Although the authors set out to use D4Ops from the very beginning, it was found that key early design decisions were based on past experience and specifically performance-based reasoning. Traditional conceptual vehicle design begins with a mission requirement such as payload to LEO or number of passengers to a moon colony. What D4Ops process suggests is that along with this mission requirement a corresponding operational design goal should be established at the start. For instance, instead of simply dictating

that Context 3a and 3b would be vertical take-off, horizontal landing, rocket-powered vehicles, the process should have begun with a D4Ops-derived operational goal (such as the vehicle shall have the minimum practical number of fluids and tanks). The combination of mission requirements and operable design requirements could then have been allowed to drive out a particular vehicle architecture and geometry.

The authors also learned more specific lessons about the concept of modularity in conceptual vehicle design. During the brainstorming sessions that preceded the development of Context 3, the idea that modular vehicle systems might enhance operability gained support. What was interesting was to watch how the implementation of modular design evolved in the Context. Early thoughts that the main propellant tanks could be designed to resemble the Space Shuttle EDO pallets were dismissed when faced with the geometric reality of accommodating the required fluids. Then when thoughts turned to dividing the main propellant volume into smaller cylinders that could presumably be removed through an opening in the aeroshell, the perceived operational benefits seemed to evaporate. Only when the modular approach was mated with the conformal tanks and deleted aeroshell was the anticipated result achieved. Perhaps the greater lesson to be learned from the modularity experiment is that had the vehicle configuration and geometry not be predetermined before thoughts of D4Ops approaches were put into action, the question would not have been: How do we make modularity work on this architecture but rather: What architecture will enable the best implementation of modularity? The answer to the second question would have revealed to the fullest extent the impact of this particular enhanced operability result.

## Chapter 8 – Conclusions

### 8.1 GENERAL OBSERVATIONS

As the conceptual designs presented in this study indicate, application of the D4Ops approaches yielded heavier (in terms of dry and gross weight), costlier (in terms of development), but operationally better (in terms of turnaround time and recurring operational cost per flight) systems. It took time and effort to develop the first foundations of a D4Ops intuition. This study group is composed of mostly performance-oriented discipline experts and thus some members of the group had to retrain their intuition to accept the importance of certain design approaches. This took time, but as the project transitioned from one context to another, the study group became more comfortable in accepting these D4Ops design approaches. One cause of this eventual acceptance was the option given to the performance discipline experts on which approaches were derived for inclusion in each context. Obtaining this sense of ownership of the approaches by the performance oriented discipline experts is a key factor of obtaining consensus on a D4Ops approach. The study benefited by the co-location of both performance and operations discipline experts in the same geographic area which aided in discussions and brainstorming. Yet even at the end of the study, there was still some hesitancy in taking the D4Ops philosophy to its logical conclusion.

The D4Ops approaches themselves were varied in terms of the type of impacts they had on the contexts in question. Sometimes, a D4Ops approach had major implications for the entire architecture whereas some other approaches only affected smaller sub-systems. The level of fidelity of the conceptual modeling toolset was possibly also responsible for the magnitude of these effects. A specific fundamental conclusion that can be drawn from the RCA database and D4Ops approach application on Contexts 1 through 3 is that a reduction in the number of fluids carried on an RLS is beneficial to its operability. The D4Ops approaches that focused on using common fluids for various subsystems repeatedly ranked near the top of the list in terms of maximizing the Overall Evaluation Criteria (OEC). Another specific key finding from analysis of these contexts is that design approaches that address the hazards and access problems associated with closed compartments on a vehicle show promising operational improvements. The results demonstrate that while many enhanced operability design features do impose performance (i.e. weight) penalties, some approaches can provide benefits with very little penalty. Such examples include a reduction in parts count (while increasing individual component reliability) and inclusion of Propulsion-focused Integrated Vehicle Health Monitoring (P-IVHM). Separately, given the extensive nature of some of the D4Ops approaches on nearer term Contexts 1 and 2, it is speculated that adding such approaches to the current Space Shuttle orbiter would be very difficult and potentially vastly expensive. Some of these D4Ops approaches impact the top level assumptions of how these RLS architectures are designed. In the case of the Space Shuttle orbiter, major subsystems would have to be removed and new ones integrated onto the vehicle.

The D4Ops approaches were developed through a combination of qualitative and quantitative processes. The RCA database was utilized to provide an initial compilation of problem areas that could indicate new approaches to system design. Additionally, brainstorming assisted in developing more creative operational approaches. These two sets of results were combined and discussed between the study authors and NASA KSC Systems Engineering Office personnel. The current RCA database used in this study has some data integrity issues. For example, the most important item of data for each activity in the database, the item of “work content hours”, only reflects the length of time of the activity without regard to the actual amount of human time spent on the activity. Thus an activity could only require a human to initiate it and then stop it, yet the work content hours will be representative of the entire time the activity is occurring. The RCA database could also be improved by including data from other Space Shuttle missions (versus just one currently) with more detail for other processing flow functions besides the turnaround-type of activity. The peculiarities of any one mission would be damped if more case studies were available. Given these issues, there was a requirement for a final, qualitative assessment of any results from the RCA database data-mining effort.

Constraints were an ever present factor in the design of all three contexts. The top level architecture assumptions inherent in Contexts 1 and 2 (an OSP and TSTO RLS) precluded obviously some approaches from being applied or in creating a more optimum, operationally-efficient architecture. Conversely, this actually may have been beneficial in order to show the discrepancy of current design intuition and the influence of a D4Ops-oriented approach. As the State-of-Practice (SOP) designs were provided by external design groups, the authors could see the lack of D4Ops

intuition that had been applied. Even given flexibility in choosing Context 3, it was potentially too constrained to be able to handle some of the new D4Ops approaches. The study team was given flexibility in choosing some of the architectural level parameters of context 3. Yet, these assumptions (such as the choice of SSTO vs. TSTO or vertical take-off vs. horizontal takeoff) triggered automatic elimination of certain D4Ops approaches.

The conceptual level toolset used in such studies is limited in its ability to model certain D4Ops design approaches. It is difficult to model in detail something like “reduced parts count” since on a conceptual level one is only able to address this on the macro scale by modeling fewer tanks, engines, thrusters, etc. Additionally, there was some difficulty in modeling design approaches related to TPS. Assumptions of unit weight increases were used in lieu of more detailed aeroheating analysis. Even if aeroheating analysis were conducted, the conceptual nature of the rest of the performance analyses (trajectory, weights and sizing, aero, etc.) could be inconsistent in terms of model fidelity. Since the operations tools currently available are based on Space Shuttle data they may not accurately reflect benefits of various D4Ops approaches or only be able to model them in a very gross manner. However, the conceptual level tools have proven to be well-suited to model macro changes such as engine count, propellant type, or aeroshell structure.

It is recognized that Context 3 is an easier concept to operate given the single stage nature of the architecture. It is not implied or concluded here that SSTO systems are the most optimum to meet future launch requirements. The SSTO option was chosen to include a vastly different context into the mix than that seen in Contexts 1 and 2. The operations model will most certainly look favorably towards this type of processing than a TSTO context. Yet other issues such as technology development for a SSTO may still need to be addressed and clarified. Thus the SSTO context examined in this study, or even the other two contexts, are not meant to point towards a better architecture type. The objective is to show how D4Ops approaches can be applied to multiple contexts and the inclusion of such operational intuition in an RLS conceptual design process.

## **8.2 RECOMMENDATIONS AND FUTURE WORK**

The results of this study should be used to integrate the D4Ops design intuition philosophy into the nominal conceptual design process. Performance-oriented designers should be given the opportunity to learn about the importance of their top-level and subsystem decisions upon the final vehicle metrics of interest (including turnaround time, recurring operations cost, and facilities cost). Effective ways should be explored of how to integrate D4Ops thinking into the mainstream design community.

There may be a potential to examine a more revolutionary use of the D4Ops philosophy in the design process. In the nominal design process currently used in the conceptual design community, operations normally comes near the end in terms of the calculation loop. This is after the performance closure has occurred and the vehicle has been shaped and sized with resultant dimensions and weight outputs. There may be some potential follow-on activity from this project that could examine how the operations discipline could be moved forward in the design process, feeding some portion of the performance closure loop. In this scenario, the operations discipline would actually help determine vehicle level characteristics such as the geometry including the outer mold line (OML). This could be described as an inside-out scheme where subsystems are defined and integrated, reliability and maintainability are assessed, integration with mission requirements is performed, and then finally compatible vehicle mold lines (i.e. geometry) are determined. This study included some preliminary discussion with personnel at the NASA KSC Systems Engineering Office with regards to this type of readjustment of the design process. The authors believe that the Context 3B RLS shown in the study may be an initial first step towards this type of approach. For Context 3b the top level subsystem requirement for the architecture was the use of modular tanks. This top level requirement, coming directly from operational concerns, helped to actually define the mold line to some extent in the context. However, this geometric dependence could have been taken even further if specific architecture level assumptions (such as SSTO, take-off/landing modes) had not already been determined.

Both the sources of the D4Ops approaches and the subsequent modeling of them is one area of improvement. There may be a need to examine the entire flow process for these contexts (from landing to launch). Some approaches may have benefits not visible unless examining the entire life cycle operations process. Additional D4Ops approaches should be developed using similar methods of brainstorming and prioritization as described in this study. This study attempts to show how the D4Ops process can be applied in many example case studies (or contexts). Additionally,

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further work on the RCA database would be beneficial in this process. Specifically, the RCA database needs to be updated with additional data-mining. Other functions besides turnaround as indexed by NASA KSC (including Cargo Processing, Traffic Control, Launch, Landing, Integration, Depot, Support, Logistics, Ops and Management, and Expendable) could also be included in the database. Some of the D4Ops approaches can currently be modeled accurately using the latest generation of conceptual design tools. However, some approaches required updates to the modeling suite employed herein. This applies to both performance and economic (cost, operations, and safety) closure loops in the design process. Future analyses should employ either the same or slightly upgraded/modified tool sets that may be able to better model the D4Ops approaches. There may be some need to move away from the reliance on historical weight-based estimation techniques as new operational approaches are very difficult to model. Once such results are generated, the TOPSIS selection technique could be applied again at this architecture level to find the most robust portfolio of approaches across different architectures. Future analyses using the D4Ops approach should examine contexts from the same time frame for more accurate comparison of the effect of these approaches on architecture metrics. The study herein examined one context from each of three different time periods. If multiple architectures were to be examined in the same time period then optimum approaches could be determined irrespective of the architecture.

# Appendix A – Statement of Work (SOW)

## Statement of Work

**Kennedy Space Center  
Root Cause Analysis (RCA) –  
“From the Ground-up” Operability Design and Modeling for  
Future Reusable Launch Systems (RLS)**

**Revision: 2/28/03**

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## BACKGROUND

It is envisioned here that dramatically safer, lower cost, and higher flight rate access to space is possible by applying the wealth of experience gained from Shuttle launch operations. Shuttle launch operations, particularly the world's only reusable space transportation elements, the orbiters, have accumulated a vast set of ideas, lessons learned, insight and “design for ops” experience. Current work such as the Shuttle Root Cause Analysis will add further insight to quantifiably understand why previous reusable launch systems (RLS) are as costly as they are and why they take as long as they do to prepare for launch.

The application of novel, not yet studied, but extremely viable and promising options for an entirely operable reusable launch system design is now feasible based on advances in operations analysis, integrating tools, models, and in understanding design margin and sub-system ops characteristics.

The services to be obtained are to perform space transportation system design analysis focused on operations. This includes deriving designs that are analyzed and defined at a conceptual to slightly more detailed level. This includes verifying performance such as weights, sizing and trajectory for a given set of requirements such as per flight payload. This task includes building on the Shuttle RCA to identify and analyze reusable launch system designs that are first and foremost “designed for operations”. This task requires providing traceability through the analysis establishing the feasibility and issues associated with the generated designs. This task requires working familiarity and past practical experience with operations analysis tools in use by Kennedy Space Center (AATe Architectural Assessment Tool – Enhanced). This task requires working familiarity and understanding of the wealth of qualitative KSC lessons learned as they apply to launch systems. This task requires that the principal investigator(s) / proposed team be able to actually “close” (fly on the computer) a design. Closing a design requires use of the same type of tools or equivalent (e.g. CONSIZ, POST) as are used by government vehicle analysis branches so as to provide standard justification and rationale.

It is the objective of this work to build on the Shuttle RCA to develop conceptual level reusable launch system designs that are first and foremost “designed for operations”.

## OBJECTIVE

### Task 1 of 3

Engage the Shuttle RCA work (ongoing) to develop insight from the raw RCA data and analysis. This includes reviewing information and feeding insight into task 2.

**Task 2 of 3**

Derive and group technology, approaches, and “designs for ops” options into systems for eliminating the root causes of un-safe, unaffordable, unresponsive designs. Design out the causes of launch system cost and time.

This includes gathering technologies being considered or funded and identifying how each of these affects the RCA. This will nominally be done deterministically with the potential to model the impacts probabilistically. It also includes pro-actively generating and gathering a list of prioritized ops technology and or approaches that may not currently be under consideration or funded by any existing program. Ops technology in many cases will equate to flight vehicle technology such as redesigned or new flight systems. This latter area includes integrating flight sub-systems hardware, common propellants and sub-system reliability and redundancy influences. The beneficial impacts to ground operations due to these changes are the focus of study.

Some of these approaches will be based upon simulation of the sub-system to yield a quantitative origin for the impact upon the RCA while others will utilize qualitative assessment of technology impacts.

Un-explored examples of highly synergistic sub-systems integration, whose impacts will nominally be determined through simulation include:

- Common tanks for OMS and RCS commodities (Shuttle has distinct, many tanks).
- Common tanks for OMS, RCS and all Power commodities (such as a fuel cell or turbine unit propellant tanks).
- Common fluids and tanks for Main Propulsion, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics & ECLSS).
- Common / shared power, electronics, software, controllers and architecture for all engines, Guidance, Navigation and Control (GN&C) functions and Integrated Vehicle Health Management (IVHM).
- Fuel Cells energy / wastes and thermal management integration (water by-products and water spray boilers).

Un-explored examples of highly synergistic sub-systems integration, whose impacts will nominally be determined through qualitative technology assessment include:

- Common, fewer, turbo-machinery, integrated into storage tanks, feeding multiple combustion processes.
- Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces.
- Common ground and flight power management schemes (flight systems used on checkout, no ground systems for conditioning).
- Communications hardware (single elements / antennas / motors for multiple bands) and cables / interfaces and connector count.
- Structural/ aerodynamics systems and safety systems (Haz Gas and Purge, Vent and Drain-PVD) as single system, lean designs resulting in reduced or eliminated fluid systems.
- Increased system reliability and reduced parts / redundancy vs. less reliability / higher redundancy (as in Shuttle).

**Task 3 of 3**

Derive 3 reusable launch system designs based on current NASA needs and requirements.

These vehicle / systems will be matured to a point of creating schematics at a top-level, with slightly more detail than shown in Figure 1.0. This greater detail will include internal tank arrangements for sub-systems such as main propulsion, auxiliary propulsion, power and thermal management. Weights, sizing and trajectory analysis using standard code (CONSIZ or equivalent) will be used to close designs, confirming feasibility of a given payload capability.

Based on the task 1 and 2 priorities (the portions of the RCA of most interest, and the priority list of ops technology), a minimum of 2 launch system designs will be derived consistent with most current NASA needs and requirements. After the analysis of these two initial designs, a third candidate launch system will also be designed. Payload on one or all designs may be part of the trade-space as ops is designed in the interest of reducing turnaround

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time and creating a system building block optimized for yearly tonnage to orbit, not per launch. This system building block is a single reusable launch system, with a derivation required of the number of these vehicles and facilities that may be required to meet a yearly need.

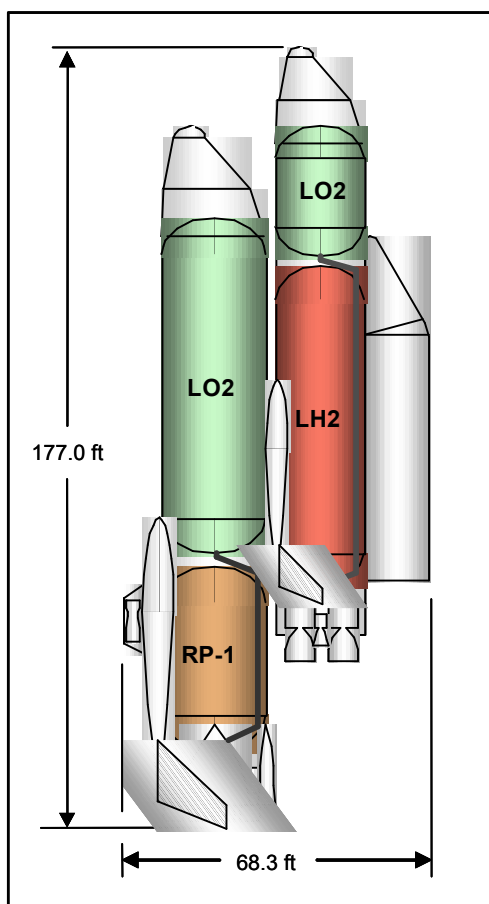


Figure 1.0 – Current Typical Schematic

## SCOPE

The contractor shall perform the tasks in close coordination with the Shuttle RCA project. RCA information will be provided by the government during the course of these tasks.

Coordination shall be made with NASA on telecons or at face to face meetings for arranging feedback and for collaborating in defining ops design options.

This includes attending (telecon) significant RCA meetings, every 2 weeks maximum.

NASA KSC will provide independent operations assessment and feedback of the resulting designs. The contractor shall provide materials in accordance with milestones to enable such analysis to be performed.

Face-to-face meetings every 3 months of the effort are required as a minimum. A final out-brief in person at KSC and MSFC is also required.

Final report shall include:

- Reusable launch system designs and operations assessment.
- Review of each “design for ops” including implications, feasibility, and well defined technical issues (e.g. a tank being used in common for power and for reaction control may require pressures in one system not be optimized so as to have overall system optimization or, alternately, a review of current system / technology limitations, such as pressures, temperatures, flow-rates, hardware weight, reliability).
- One Type Two-stage-to-orbit (TSTO) design.

- One Type Orbital Space-Plane (OSP) / Evolved Expendable Launch Vehicle (EELV) design.
- Dependent on the prior results, a Design 3 vehicle will be addressed and derived.

## **MILESTONES**

### **1 Month After Receipt of Order (ARO)**

Provide recommendations report and a plan for translating RCA information (problems) into technology, design, or ops (solutions).

### **2 Months ARO**

Finalized, prioritized list of designs, with technology or ops approaches to be studied, including definition of the degree of detail planned.

### **3 Months ARO**

Preliminary design 1. TSTO.

### **6 Months ARO**

Preliminary design 2. OSP.

### **8 months ARO**

Design 1, 2 and dependent Design 3 reusable launch systems near complete including ops assessment.  
Draft final report.

### **9 Months after ARO**

Final report and final out-briefs at KSC and MSFC.

Period of performance is up to 9 Months after award.

## **DELIVERABLES**

Detailed monthly progress report

Final summary report in MS Word format.

Final summary briefing in MS PowerPoint format.

Final detailed report of all work (all work files) in either of prior formats.

Weight statements

Analysis (spreadsheets).

Detailed description of operability features

## Appendix B – Description of Disciplinary Models

The following are description of engineering disciplinary models used for the analyses on Contexts 1, 2, and 3:

- CAD/Solid Modeling
- Preferred Tool: Solid Edge V14

The CAD modeling entailed creation of outer mold line geometry (OML) and internal component layout for each of the contexts. Examples of modeled internal components include main propellant tanks, OMS and RCS propulsion tanks, landing gear, propulsion systems (main, OMS, RCS), payload bay, and approximate subsystem volumes and locations (e.g. avionics, APUs, batteries, ECLSS). The primary outputs from the CAD modeling were reference, or as-drawn, component volumes, surface areas, and location.

- Mass Properties
- Preferred Tool: Microsoft Excel Spreadsheet

The system weights were determined using a combination of results from higher level analysis (e.g. avionics sizing, propulsion) and the standard industry practice of mass estimating relationships (MERs) for subsystems and appropriate average unit weights for vehicle structures (e.g. wings, airframe, tanks). Vehicle sizing was accomplished through photographing scaling about the reference vehicle.

- Trajectory
- Preferred Tool: Program to Optimize Simulated Trajectories (POST) ver. 5.102

The trajectory simulation consisted of a three degree of freedom (3DOF) analysis for Contexts 2 and 3 starting at time zero to the desired final orbit. Input parameters to the system included the aerodynamics database with Mach number and angle-of-attack dependency, propulsion system with multiple independent variables, stage weights, and normal force load limits.

- Aerodynamics
- Preferred Tools: (low speed) existing configuration databases; (high speed) Supersonic/Hypersonic Arbitrary Body Program (S/HABP) Mark 5

For the low-speed aerodynamic performance (Mach 0 to 2), lift and drag estimates from prior work done for similar vehicle configurations was applied (eg. ACRE-92 WB001 concept).

High-speed aerodynamic performance was determined using the S/HABP program. This NASA-developed tool, which uses Newtonian impact theory (e.g. tangent cone, tangent wedge) with engineering-derived friction and heating models, is the industry standard code for generating lift and drag coefficients in the Mach 2+ flight regime during conceptual design studies. The code generates tables of aerodynamic coefficients as functions of flight Mach number and angle-of-attack.

- Rocket Propulsion
- Preferred Tool: Rocket Engine Design Tool for Optimal Performance (REDTOP) v1.0

REDTOP is a conceptual-level engineering design and analysis tool developed by SEI for the performance prediction of liquid propellant rocket engines. The tool is written in the object-oriented C++ programming language. REDTOP can be executed through its Graphical User Interface (GUI) on PC platforms or via Phoenix Integration's Model Center© (MC) environment with its Analysis Server© (AS) fileWrapper. The AS© fileWrapper allows for automated execution and direct integration with other disciplinary analysis tools (e.g. trajectory, mass properties, etc.).

REDTOP can support a wide variety of liquid rocket engine configurations. In addition to the built-in propellant options, the chemical equilibrium routine is capable of handling any generic fuel and oxidizer combination. Numerous options exist for sizing an engine, including thrust and throat area matching. An ‘expert system’ of engine efficiencies is also included, allowing for cycle, chemical reaction, injector/combustor, and nozzle influences on performance. This allows REDTOP to accurately predict real engine performance.

- Operations
- Preferred Tool: AATe (Architecture Assessment Tool-enhanced)

The Architectural Assessment Tool – enhanced (AATe) is a tool for assessing a space transportation system for its operational impacts, mainly costs and cycle times. It is capable of providing both qualitative and quantitative insights into systems still being conceptualized. The tool is based on the work of both the national Space Propulsion Synergy Team (SPST) and of the joint NASA, Industry & Academia Vision Spaceport project. This model requires both quantitative inputs and qualitative order of magnitude comparisons of the concept vehicle to the Space Shuttle. Inputs include: overall vehicle reliability, airframe life, payload weight, dry weight, vehicle length, and payload demand per year. Outputs include: ground turnaround time, facilities cost, labor cost per flight, line replaceable unit (LRU) cost per flight, and operating expenses per flight.

- Non-Recurring Cost
- Preferred Tool: NASA Air Force Cost Model (NAFCOM) Cost Estimating Relationships, Excel

Non-recurring costs include Design, Development, Testing, and Evaluation (DDT&E) and Theoretical First Unit (TFU) costs. This Excel based model uses subsystem weight-based cost estimation relationships (CER’s) sourced in part from data within NASA’s unrestricted release version of NASCOM database II6. DDTE & TFU includes a common weight breakdown structure. Currently, CER’s for the level 1 breakdown are available. The propulsion system is treated separately since it is commonly acquired separately from the airframe subsystems. Currently, weight breakdown structure and CER’s are provided for up to three main vehicle stages. Programmatic costs include: system test hardware; integration, assembly, & checkout; system test operations; ground support equipment; systems engineering & integration; and program management. Cost margins are normally applied to all

- Reliability and Safety
- Preferred Tool: GTSafetyII, Excel

GTSafetyII is a top-level MS Excel based spreadsheet for determining various safety and reliability metrics for reusable launch vehicles (RLVs). The model requires both quantitative inputs from other RLV disciplinary tools (referred to as coupling variables) as well as specific qualitative user inputs as to the architecture being examined (including safety adjustment factors). The coupling variables consist of variables that describe the physical dimensions of the vehicle (wetted area, length, height, etc.), the configuration (number of propulsion systems, etc.), and the use of the vehicle in the program (flights per year, passengers per flight, etc.). The other types of variables are used for qualitative comparisons of the vehicle in question with the space shuttle. The additional safety calculations are separated into the following areas: public/collateral safety, ground personnel safety, flight crew/passenger safety, TPS reliability, engine reliability, overall mission/vehicle reliability calculations. Overall metrics are then determined related to both vehicle reliability and program safety. The reliability metrics include terms for both loss of mission and loss of vehicle. The safety metrics include for casualty rate and loss of crew events. Output metrics are listed at the top of worksheet and are shown in terms of both flights between incidents and years between incidents.

## Appendix C – Brainstorming D4Ops Approaches

Note: the following are various approaches arrived at in the brainstorming session:

- Reduce unique TPS parts count (besides #8 from prime list), see Frank Jones
- Vehicle Mirroring (TPS identical left and right sides...reduce unique parts count)
- TPS approach at access areas (standard? More robust / material select / framing / metallics).
- Windward blankets or metallics
- More concern about TPS moldline penetration and repair/replacement (self-healing TPS including self-healing seals)
- All-weather capability
- Eliminate waterproofing...how?
- Wireless power transmission
- Self-ferry and power landing
- Extensive use of high storage density batteries in place of fuel cells and APU's (replace hydraulic/pneumatic systems with EMAs)
- More resilient window treatment/environment (alternatively reduction in total window surface area)
- Margin as a factor (increased Safety Factors)
- Propulsion margin (de-rate X% power level)...add life to engines / components.
- Soft start engine sequence
- Power-head cycle selection...e.g. expander cycle by it's design
- IVHM...propulsion focus especially
- Layout of tanks
- LOX tank aft (ground-rule)
- Both tanks aft?
- Pumps at tanks - de-integrated engines, integrated main propulsion (tankage/pumps then chambers)
- Layout of engines (spaced for maintainability)
- No center engine (no pogo?)
- Fiber optic cabling vs. Cu / Aero type (kapton)...FI connectors?
- Non-cryogenic propellants
- Fluid selection
- LOX/LH2 - baseline
- Ocon vs. Tcon 6 month stay issue (cryo-coolers?)
- Zero g
- Verify OMS thrust
- Verify RCS thrusts
- Verify power capacity
- Layout - 2? Pods? (more Tcon applicable)
- OX as N2O2 (gas)
- No windows...virtual cockpit
- No actual cockpit...just a passenger compartment, minimal monitor views
- Integrated power and comm. cabling (same cable)
- Wireless informed maintenance
- Payload containers / architectures (internal v. external)
- Reduced engine count - larger, fewer engines for main
- Relight main engines for OMS
- Return inverted
- No aeroshell
- Landing gear...number of tires / materials
- Ablative TPS
- LOX rich / added thrust at lift off / variable mixture ratio

**Table C.1. List of Operational Approaches Available For QFD Process**

Approach Number	Approach Type	Approach Name
1	Integration of Functions	Reduce parts count using highly reliable parts (vs. less reliability in the parts and higher need for redundancy as in Shuttle).
2	Vehicle Configuration	Place oxidizer tanks in aft vehicle location to minimize fill pumping requirements
3	Vehicle Configuration	Place both oxidizer AND fuel tanks in aft vehicle location (toriod solution) to reduce feedlines and standardize fill/drain locations
4	Vehicle Configuration	Use external payload containers to allow off-line payload integration
5	Vehicle Configuration	Include self-ferry and power landing to reduce delays associated with non-KSC landing
6	Vehicle Configuration	Create symmetrical layout of main engines (spaced for maintainability)
7	Vehicle Configuration	Include improved access to vehicle areas (including TPS approaches) including more robust cutout material selection and framing
8	Vehicle Configuration	Fly return trajectory inverted to minimize penetrations of windward TPS system
9	Vehicle Configuration	Design for no center engine placement (reduced pogo effect, no difficult access)
10	Vehicle Configuration	Reduce number of flight elements (fewer flight stages)
11	Vehicle Configuration	Eliminate crossfeed between flight elements
12	Vehicle Configuration	Reduce tank count
13	Vehicle Configuration	Include IVHM system for structural and thermal loads monitoring
14	Vehicle Configuration	Eliminate external aeroshell and closed compartments
15	Vehicle Configuration	Design to allow horizontal processing of flight elements
16	Propulsion	Eliminate all hypergols in favor of LOX/LH2 propellant combination for ACS
17	Propulsion	Eliminate hypergols AND cryogenic ACS propellants in favor of "green" non-cryogenic ACS propellants
18	Propulsion	Engine pumps located at tanks - de-integrated engines, integrated main propulsion (tankage/pumps then chambers)
19	Propulsion	Eliminate need for hypergolics by using alternate, "green" on-orbit long life propellants
20	Propulsion	Reduce and/or eliminate gaseous helium as pressurant in favor of self-pressurizing or pre-pressurized blow-down ACS tanks
21	Propulsion	Reduce engine count (use larger, fewer engines for main/OMS/RCS)
22	Propulsion	Add additional propulsion margin (typically a de-rated power level to add life to engines / components)
23	Propulsion	Use a longer, but soft start main engine sequence prior to liftoff
24	Propulsion	Choose a lower-pressure open engine power-head cycle (e.g. gas-generator or tap-off) vs. a higher lsp closed power-head cycle (staged combustion, expander)
25	Propulsion	Eliminate need for separate OMS engines by using throttled MPS on-orbit
26	Propulsion	Use a Variable Mixture Ratio LOX/LH2 MPS to increase bulk density and reduce tank size
27	Structures and Mechanisms	Use more resilient window treatments to reduce the need to polish windshield panes
28	Structures and Mechanisms	Reduce or remove total window surface area using techniques such as a virtual cockpit
29	Structures and Mechanisms	Use better and sturdier landing gear in terms of number of tires and materials
30	Structures and Mechanisms	Add structural margin to airframe design to increase robustness and reduce inspection requirements
31	Thermal Protection System (TPS)	Use a left-right symmetric TPS (TPS identical left and right sides and reduce unique parts count)
32	Thermal Protection System (TPS)	Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces.
33	Thermal Protection System (TPS)	Eliminate/reduction of TPS waterproofing requirement
34	Thermal Protection System (TPS)	Use of one-time ablative TPS panels rather than reusable tiles
35	Thermal Protection System (TPS)	Reduce TPS moldline penetration and repair/replacement (self-healing TPS including self-healing seals)
36	Subsystems	Use wireless power transmission to power vehicle on ground (rather than power umbilicals)
37	Subsystems	Make extensive use of high storage density batteries in place of fuel cells and APU's
38	Subsystems	Streamline and combine communications hardware (single elements / antennas / motors for multiple bands) and cables / interfaces and connector count.
39	Subsystems	Use fiber optic cabling throughout versus current Cu/Aero type (Kapton)
40	Subsystems	Incorporate Propulsion-focused IVHM
41	Subsystems	Replace hydraulic/pneumatic systems with EMAs

Approach Number	Approach Type	Approach Name
42	Subsystems	Eliminate toxic fluids in ECLSS and thermal management systems
43	Integration of Functions	Use common tanks for OMS and RCS commodities (Shuttle has distinct, many tanks).
44	Integration of Functions	Use common tanks for OMS, RCS AND all Power commodities (such as a fuel cell or turbine unit propellant tanks).
45	Integration of Functions	Use common fluids AND tanks for Main Propulsion System, OMS, RCS and Power
46	Integration of Functions	Use common fluids and tanks for Main Propulsion System, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics, and ECLSS)
47	Integration of Functions	Use common requirements/ shared power, electronics, software, controllers and architecture for all engines, Guidance, Navigation and Control (GN&C) functions and Integrated Vehicle Health Management (IVHM).
48	Integration of Functions	Reduce pumping turbo-machinery systems by integrated into storage tanks, feeding multiple combustion processes
49	Integration of Functions	Integrate Fuel Cell products of reaction (water) and thermal management system (water spray boilers/evaporators).
50	Integration of Functions	Use common ground and flight power management schemes (actual flight systems used on checkout, no ground systems for conditioning).
51	Integration of Functions	Integrate structural/ aerodynamics systems and safety systems (Haz Gas and Purge, Vent and Drain-PVD) as single system, lean designs resulting in reduced or eliminated fluid systems.
52	Integration of Functions	Combine power and comm cabling for umbilicals and internal routing (same cable)

## Appendix D – Context 1 Supporting Material

Table D.1. List of Selected D4Ops Strategies and Design Approaches

Design4Ops Strategy	Work Content Potential Reduction Through Use of D4Ops Strategy (Total RCA Direct Work Contribution)	Selected Design Approach	Assessed Benefit (RCA Direct Work Content Reduction)
INTEGRATE PROPULSION SYSTEMS	Liquid Propulsion Work Content (14.5% Max Contribution)	Reduce engine count (use larger, fewer engines for main/OMS/RCS, i.e. Eliminate need for separate OMS engines by using throttled MPS on-orbit)	
		Eliminate all hypergols in favor of LOX/LH2 propellant combination for ACS	
		Eliminate hypergols AND cryogenic ACS propellants in favor of "green" non-cryogenic ACS propellants	
		Incorporate Propulsion-focused IVHM	
INTEGRATE POWER MANAGEMENT FUNCTIONS	Power Management Work Content (10.9% Max Contribution)	Simpler, all-electric power and actuation system (use EMAs/EHAs at load and use high storage density batteries in place of fuel cells and APU's, replace plumbing with wiring)	
IMPROVE PASSIVE THERMAL MANAGEMENT	Thermal Management Work Content (10.7% Max Contribution)	Uniform, exactly identical and interchangeable TPS parts for high percentages of vehicle surfaces	
		Reduce TPS moldline penetration and repair/replacement (self-healing TPS including self-healing seals)	
INTEGRATE ACROSS PROPULSION & AIRFRAME	Liquid Propulsion/Structures, Mechanisms & Veh Handling (48.2% Max Contribution)	Eliminate external aeroshell and closed compartments, Integrate structural/ aerodynamics systems and safety systems (Haz Gas and Purge, Vent and Drain-PVD) as single system, lean designs resulting in reduced or eliminated fluid systems.	
INTEGRATE ACROSS PROPULSION & POWER FUNCTIONS	Liquid Propulsion/Power Mgmt (25.4% Max Contribution)	Use common fluids AND tanks for Main Propulsion System, OMS, RCS and Power	
INTEGRATE ACROSS PROPULSION, PWR & THERMAL MGMT FUNCTIONS	Liquid Prop/Power/Thermal Mgmt (36.1% Max Contribution)	Use common fluids and tanks for Main Propulsion System, OMS, RCS, Power and Thermal Management (heat loads, cooling, warming, avionics, and ECLSS)	
INCREASE OVERALL SYSTEMS RELIABILITY	Unplanned Work Content (24% Max Contribution)	Reduce parts count using highly reliable parts (vs. less reliability in the parts and higher need for redundancy as in Shuttle)	

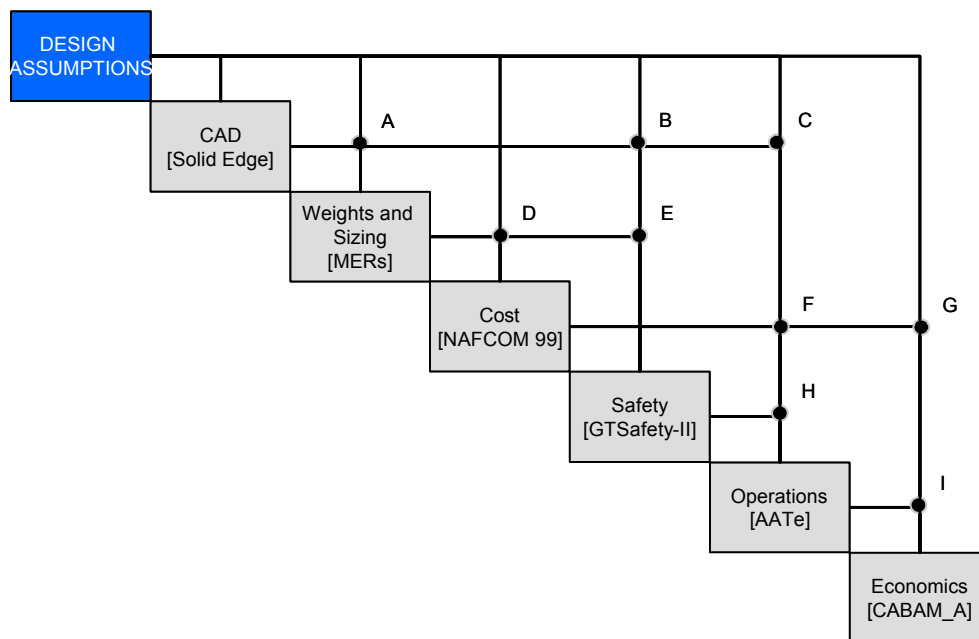


Figure D.1. Design Structure Matrix (DSM) of Assessment Process

Feed Forward Links

- A: Wing Exposed Planform Area [ft<sup>2</sup>]  
 Total Exposed Wingspan (less fuselage width)  
 Total Tail Planform Area [ft<sup>2</sup>]  
 Nose Structural Surface Area [ft<sup>2</sup>]  
 Midbody Surface Area (less cabin) [ft<sup>2</sup>]  
 Base Area [ft<sup>2</sup>]  
 ACC Leading Edges Length (total)  
 AETB-8 Wetted Area [ft<sup>2</sup>]  
 AFRSI Wetted Area [ft<sup>2</sup>]
- B: Total Vehicle Length [ft]  
 Total Vehicle Height-w/o landing gear down [ft]  
 Total Vehicle Width [ft]  
 Total Vehicle Wetted Area [ft<sup>2</sup>]
- C: Total Vehicle Length [ft]  
 Total Vehicle Height-w/o landing gear down [ft]  
 Total Vehicle Width [ft]
- D: Dry Weights [lbs] from 14 categories
- E: Total Propellant Weight [lbs]  
 Total Number of OMS Engines
- F: Total Development Cost [\$B]
- G: DDT&E Cost [\$B]  
 TFU Cost [\$B]
- H: Vehicle Reliability
- I: Recurring Operations Cost per Year [\$M]  
 Recurring Operations Cost per Flight [\$M/Flight]  
 GSE Operations Cost [\$M]  
 Turnaround Time [days]  
 Vehicle Reliability

**Figure D.2. List Design Structure Matrix (DSM) Links of Assessment Process****Table D.2. D4Ops Context 1: Design Assumptions (1 of 3)**

Design Category	Context Properties
Mission	<ul style="list-style-type: none"> <li>- Fully reusable, winged-body Orbital Space Plane</li> <li>- Initial Operating Capability (IOC) of 2012</li> <li>- Based on top of a Boeing Delta IV Heavy booster</li> <li>- 4 Crew and 500lbs payload up-lift capability</li> <li>- On-orbit delta-V requirement set at 1,500 ft/s (Source: JSC)</li> </ul>
Source / Heritage	<ul style="list-style-type: none"> <li>- Original source OSP developed by NASA Johnson Space Center (JSC), Baseline JSC Feasibility Trade</li> <li>- Relies on X-38 heritage for many subsystems</li> <li>- Date of Input Design: January 2003</li> <li>- Contact: Edgar Zapata (NASA KSC)</li> <li>- Contact: Chuck Dingell, Deputy Chief Engineer, EA3, JSC Engineering (NASA JSC)</li> </ul>
Configuration	Booster: - Delta IV Heavy  Orbiter: - Lifting Body with Wing - Rocket Powered

Table D.3. D4Ops Context 1: Design Assumptions (2 of 3)

Design Category	Context Properties
Propulsion	<ul style="list-style-type: none"> <li>- Packaged MMH/NTO for Orbital Maneuvering System (OMS) and Reaction Control System (RCS)</li> <li>- 6 OMS engines at 200 lbf thrust each</li> <li>- 24 aft RCS engines at 50 lbf thrust each</li> <li>- 14 fwd RCS engines at 50 lbf thrust each</li> <li>- Delta-V = 1500 ft/sec (Space Shuttle carries ~1100 – 1300 ft/sec)</li> </ul>
Structures	<ul style="list-style-type: none"> <li>- Airframe construction is basic Aluminum 2219 and 2024, no composites on the airframe</li> <li>- Propellant and pressurant tanks are based on Titanium overwrapped with Graphite</li> </ul>
Thermal Protection System	<ul style="list-style-type: none"> <li>- Little tile shape commonality</li> <li>- Waterproofing required on all</li> <li>- ACC Leading Edges</li> <li>- AETB-8/TUFI tiles</li> <li>- FRSI/AFSI blankets</li> </ul>
Power Generation	<p>Low voltage</p> <ul style="list-style-type: none"> <li>- 28VDC PEM Fuel Cells (3.5KW average capability each, 7kW assumed total vehicle average power, Qty 4)</li> <li>- LH2/LO2 reactant for 5 days (LO2 also supplies ECLS)</li> <li>- Cryo coolers to prevent boiloff while docked at ISS</li> <li>- 28VDC batteries (Silver-Zinc, sized only for startup, ~15 min of vehicle)</li> </ul> <p>High voltage</p> <ul style="list-style-type: none"> <li>- Used for surface EMA's, CES motor EMA's, parafoil winches</li> <li>- 270VDC Li-Ion batteries (Qty 3)</li> <li>- Sized based on X-38 re-entry power/energy requirements (each battery sized for full mission)</li> </ul>

Table D.4. D4Ops Context 1: Design Assumptions (3 of 3)

Design Category	Context Properties
ECLS (Environmental Control and Life Support)	<p>Essentially X-38/CRV system with changes (Same basic fault tolerance approach as shuttle):</p> <ul style="list-style-type: none"> <li>- Replacement of LIOH/mol sieve canisters with regenerative system</li> <li>- Addition of freon radiators (min 400 sqft area)</li> <li>- Deletion of GO2 tanks (winged and LB) in favor of Fuel Cell LO2 supply</li> </ul> <p>Active Thermal Control System:</p> <ul style="list-style-type: none"> <li>- External freon loops (single phase) and radiators (7+2.4 KW heatload assumed)</li> <li>- Internal water loops</li> <li>- Water sublimators for on-orbit cooling while radiators not exposed to space</li> <li>- Freon used in sublimator for sea-level evaporant (post landing)</li> </ul> <p>Atmospheric Revitalization System:</p> <ul style="list-style-type: none"> <li>- Cabin air loop</li> <li>- Regenerative CO2/H2O removal system</li> <li>- Non-condensing cabin heat exchanger</li> </ul> <p>Cabin pressure control system:</p> <ul style="list-style-type: none"> <li>- GN2 high pressure storage</li> <li>- Uses fuel cell LO2 reactant for O2 makeup (capsule CM requires addt of GO2 bottle)</li> <li>- Flight computers regulate pressure/PPO2 based on sensor readings and control of valves</li> <li>- Cabin vent (purge) valves to cover CRV medical mission scenarios</li> <li>- Cabin pos/neg pressure relief valves</li> </ul>
Additional Subsystems	<p>Electromechanical Actuators (EMA):</p> <ul style="list-style-type: none"> <li>- Used for winged vehicle aerosurface control</li> <li>- Based on X-38 flap and rudder actuators</li> </ul> <p>Pyrotechnics:</p> <ul style="list-style-type: none"> <li>- Functions (Spacecraft separation, CES separation &amp; activation, Parachute mortars, Parachute strap cutters, Landing gear/bag panel deploy, Emergency hatch jettison)</li> <li>- Assumed to be laser-initiated</li> </ul>

Table D.5. D4Ops Context 1: SOP Operations Assumptions (1 of 4)

AATe Input Category	AATe Input
<u>ARCHITECTURE INPUTS</u> Basis for Fleet Calculations	Demand per Year
<u>ARCHITECTURE INPUTS</u> Demand (MLBs) or Flights per Year	4.0
<u>ARCHITECTURE INPUTS</u> Stacked Dimensions	16 ft: System Envelope-Length (feet) 49 ft: System Envelope-Width (feet) 256 ft: System Envelope-Height (feet)
<u>ARCHITECTURE INPUTS</u> Costs	15.00: Estimated Development Cost (FY2000\$B) 20: Life of the Debt, for "Upfront Costs or, if "Zero Cost of Money, Operating Life [years] 5.00%: Cost of Money for 1&2 plus Facility/GSE Acquire [%] 5.00%: Insurance [per Flight as % of Vehicle Cost]
<u>ARCHITECTURE INPUTS</u> Spaceport Architecture	3: Human Focused Systems
<u>ARCHITECTURE INPUTS</u> Vehicle Paths	Vehicle Turnaround: 1: (STS) Go to a dedicated Turnaround Facility(s), Single or Multi-Stage Reusable Vehicle Assembly/Integration: 6: Single Stage Vehicle - No Element Assembly/Integration Required
<u>ARCHITECTURE INPUTS</u> DYNAMIC EVENTS (Q3)	Main propulsion operating dynamic events & operating modes excluding start-up & final shutdown (e.g., staging, mixture ratio changing, throttling, mode changes like low speed to high speed system): 3: STS) Multi-stage separation, throttling & early single engine shutdown dynamics
<u>ARCHITECTURE INPUTS</u> MAINTAINABILITY (Q10)	Space transportation maintainability (on-line operation, not depot-level repair): 4: Single-stage vehicle architecture that requires compartment entry, ground supplied purge system in air mode, installation of access platform hardware, removal of another system's components (which now lose their certification for flight) in order to gain access - all of the above only doable after vehicle is drained of propellant and "safed" (e.g., propellant tank and compartment purges, separation ordnance safely disarmed, etc.)

Table D.6. D4Ops Context 1: SOP Operations Assumptions (2 of 4)

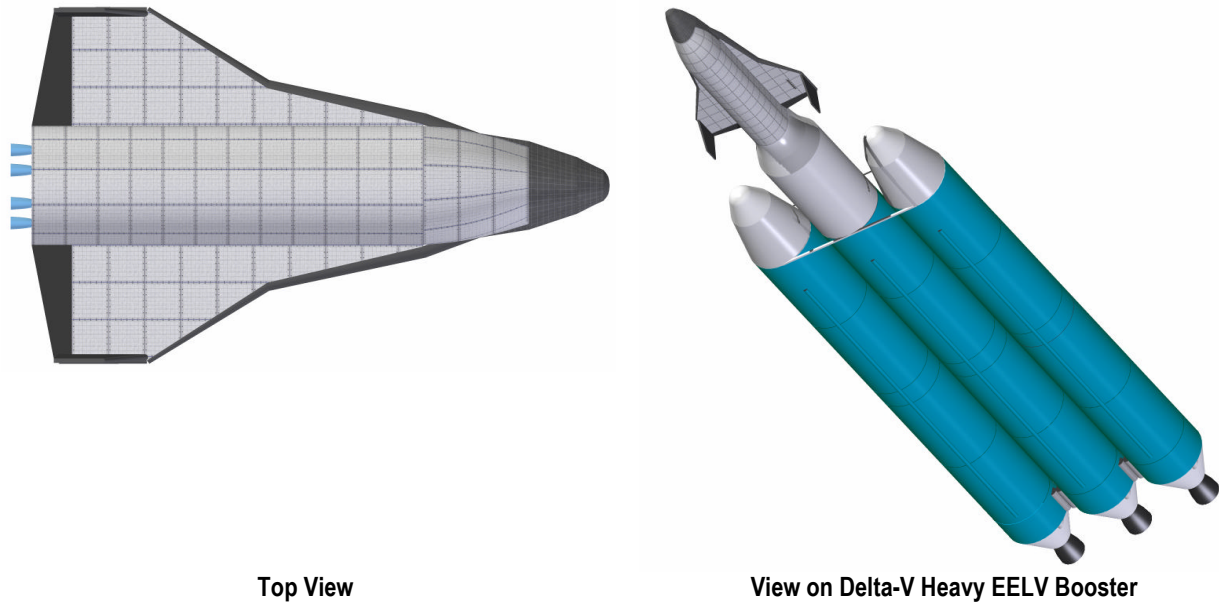
AATe Input Category	AATe Input
<u>ELEMENT/STAGE INPUTS</u> Dimensions	0.9994800: Targeted Reliability, Value for Loss of Vehicle (e.g. 0.9999) (Also see Q6) 100: Stage Design Life (e.g. 1000 Flights) (Also see Q18) 5: Time in orbit [days] 0.00: Payload in Stage 1: Number of Stage (First=1, Second=2, etc.)  STAGE 55.665 lbs: Weight (insertion, minus payload) [klbs] (Note for State of Practice) 46 ft: Length [feet] 28 ft: Width [feet] 13 ft: Height [feet]
<u>ELEMENT/STAGE INPUTS</u> Cost and Objective	3.00: Estimated Stage/Element Cost (FY2000\$B) Expendables, Payload & Crew 5: E - Reusable, NO Payload or external, +Active Crew/Cockpit Type.
<u>ELEMENT/STAGE INPUTS</u> INTEGRATION PROPULSION (Q1)	Q1. Overall propulsion packaging architecture—(DF#6): 2: Partially integrated propulsion systems 1: ENABLE LEVEL 2 ANALYSIS [0=NO, 1=YES]  A) Engines (CHECK ONLY THOSE APPLICABLE; VALID COMBINATIONS ARE: 1+3, 2+3, 1+4, 2+4, 3, or 4): 4: (STS) Dedicated stand-alone main engines; OMS is separate (or n/a, per 1 above). B) Tanks (CHECK ONLY THOSE THAT ARE APPLICABLE): OMS and RCS feed off of same propellant tanks. No separate RCS tanks. C) Liquids, tank count, MPS, OMS, RCS, power, thermal management, (i.e. plumbing complexity) (CHOOSE ONLY ONE): Between 10 and 20.
<u>ELEMENT/STAGE INPUTS</u> GENERAL PROPULSION (Q2)	0: No main propulsion engine element in this stage

Table D.7. D4Ops Context 1: SOP Operations Assumptions (3 of 4)

AATe Input Category	AATe Input
<u>ELEMENT/STAGE INPUTS</u> MATERIALS (Q4)	4: (STS) Architectural concept requires use of pollutive or toxic materials on the flight vehicle, but may use a few during manufacturing, assembly, cleaning & ground servicing operations—into the atmosphere during flight, and requires much cleanup at launch site following launch (along with toxic waste management and disposal)
<u>ELEMENT/STAGE INPUTS</u> INTERFACES (Q5)	4: (STS) Multiple stages with many interfaces
<u>ELEMENT/STAGE INPUTS</u> RELIABILITY (Q6)	4: (STS) Uses only custom minimum weight components
<u>ELEMENT/STAGE INPUTS</u> FAILURES (Q7)	4: (STS) Transportation system has many "Criticality 1" failure modes (accepted by rationale), accepts loss of mission, and additionally accepts loss of vehicle (1:500 flights probability)
<u>ELEMENT/STAGE INPUTS</u> ACTIVE SYSTEMS (Q8)	4: (STS) Vehicle requires many active components to function during flight—requires several systems to maintain safe vehicle (i.e., not-fail safe)—contains many systems that require monitoring due to hazards which require corrective action to "safe" the vehicle.
<u>ELEMENT/STAGE INPUTS</u> INTEGRATION (Q9)	4: (STS) Space Transportation that's extremely complex—i.e., has multiple stages and no integration of similar or like functions to reduce number of systems and components—results in many systems and a very large ground support infrastructure with a very high parts count.
<u>ELEMENT/STAGE INPUTS</u> FLUID/TOXIC (Q11)	4: (STS) Uses some toxic fluids for flight and ground operations
<u>ELEMENT/STAGE INPUTS</u> FLUIDS (Q12)	<p>Number of different fluids &amp; flight vehicle-to-ground interfaces — (DF#8, 12):</p> <p>3- Single stage vehicle with fully integrated propulsion design that only requires two fluids and stored in two tanks, but has separate system(s) for other fluid system functions (e.g., active cooling)</p> <p>1: ENABLE LEVEL 2 ANALYSIS [0=NO, 1=YES]</p> <p>1: Ammonia (NH3) (e.g. like STS for thermal management, heat from the Freon-21 loops below 100,000 feet until ground cooling is turned on).</p> <p>1: DMES, Waterproofing Agent (e.g. like STS for ceramic TPS tile &amp;/or blankets, like STS)</p> <p>1: Freons R-21 (e.g. like STS for thermal management on board the vehicle, indirect and direct cooling of avionics, crew cabin, and fuel cells and warming/cooling of hydraulics on orbit)</p> <p>1: Freons R-22 (e.g. like STS for the ground coolant refrigeration module after the ammonia boilers are turned off, pre-launch and post landing).</p> <p>1: Freons R-114 (e.g. like STS in the orbiter payload coolant loop as well as the ground coolant unit circulation module)</p> <p>1: Hypergolic / Fuel / MMH / MonoMethylHydrazine (e.g. like STS OMS/RCS)</p> <p>1: Hypergolic / Oxidizer / N2O4 / Nitrogen-Tetroxide (e.g. like STS OMS/RCS)</p> <p>1: LH2 (e.g. like STS)</p> <p>1: LOX / Propellant Grade (e.g. like STS)</p>

Table D.8. D4Ops Context 1: SOP Operations Assumptions (4 of 4)

AATe Input Category	AATe Input
<u>ELEMENT/STAGE INPUTS</u> GASES (Q13)	5: (STS) Multiple-stage that requires many different gases for flight operations (e.g., GH2, GO2, GHe, GN2, NH3, etc.) which are stored in many separate vessels and each requiring flight-to-ground interfaces for servicing
<u>ELEMENT/STAGE INPUTS</u> ELECTRICAL (Q14)	3: (STS) Many vehicle ground power systems required (multi-voltages, dc/ac, single-phase, multi-phases, etc.) resulting in large ground power infrastructure
<u>ELEMENT/STAGE INPUTS</u> HEALTH MANAGEMENT (Q15)	4: All systems—both passive and active—have BIT/BITE from on-board, with limited use of intrusive sensors, requiring limited hands-on or ground support aided activity—utilizing an architecture with minimum number of conductor paths, connectors, interfaces, etc.
<u>ELEMENT/STAGE INPUTS</u> CONNECTIONS (Q16)	4: (STS) Traditional techniques are used that require leak checks (i.e., process controls) and many fittings and flanges are used for ease of assembly
<u>ELEMENT/STAGE INPUTS</u> PURGES (Q17)	4: (STS) Flight vehicle contains several closed compartments, removable heat shields, and ground support systems to provide environmental control, both on the ground and in flight
<u>ELEMENT/STAGE INPUTS</u> MARGIN (Q18)	3: (STS) Lack of performance margin (required mass fraction) in the system, such that robustness and responsiveness are compromised on features such as on-board BIT/BITE VHM, subsystem simplicity, robust thermal protection (has negative operational margin)



Top View

View on Delta-V Heavy EELV Booster

Figure D.3. D4Ops Context 1: Design Approach 0 (State-of-Practice)

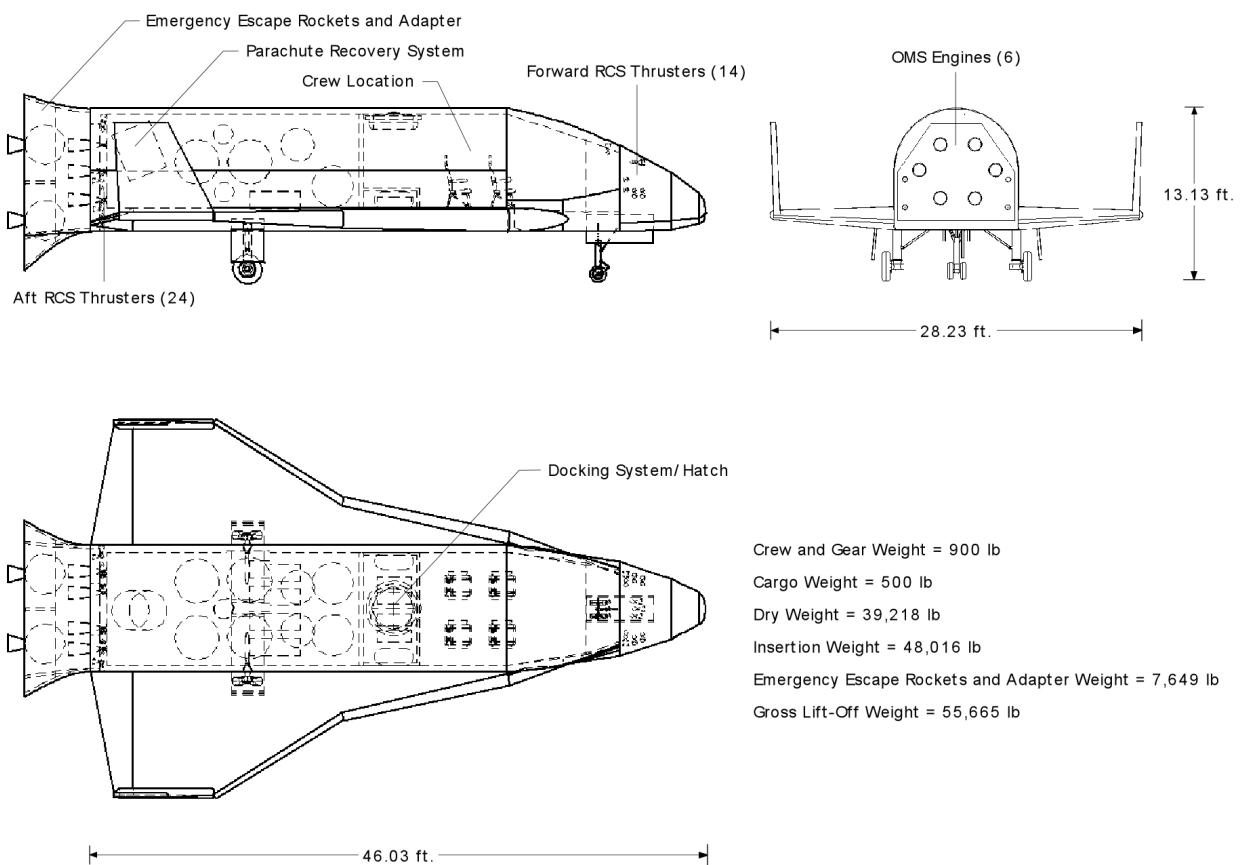
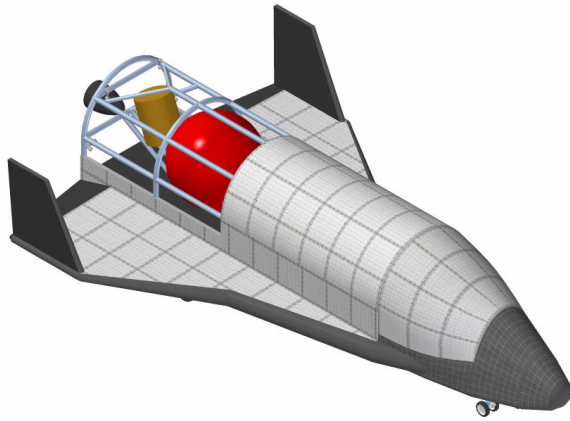
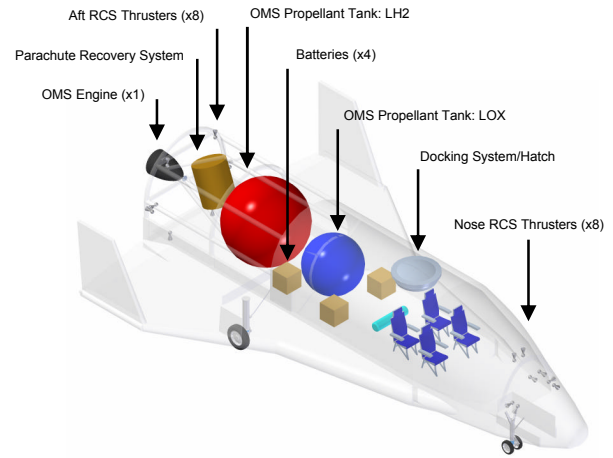
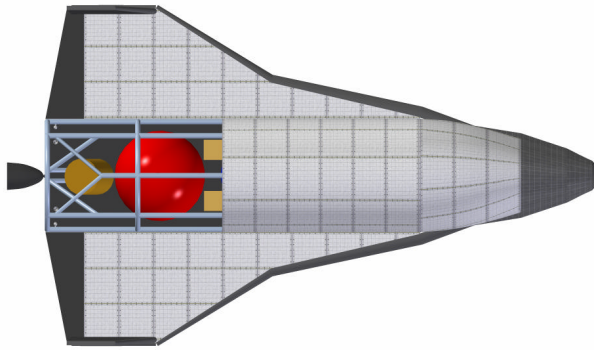
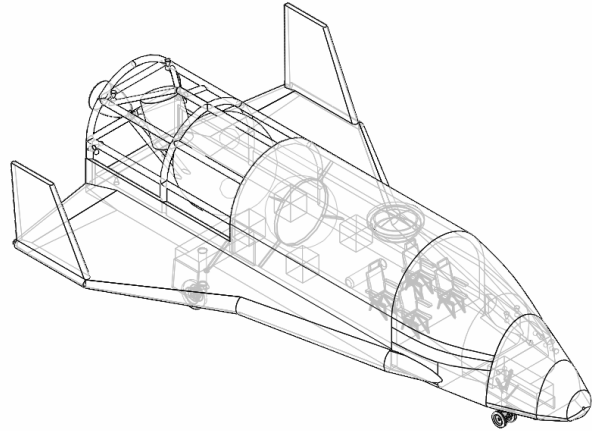


Figure D.4. Context 1 Three View: Design Approach 0 (State-of-Practice)

**External View****Internal Packaging View****Figure D.5. D4Ops Context 1: Design Approach 12 (Roll-Up)****Top View****Internal Schematic View****Figure D.6. D4Ops Context 1: Design Approach 12 (Roll-Up)**

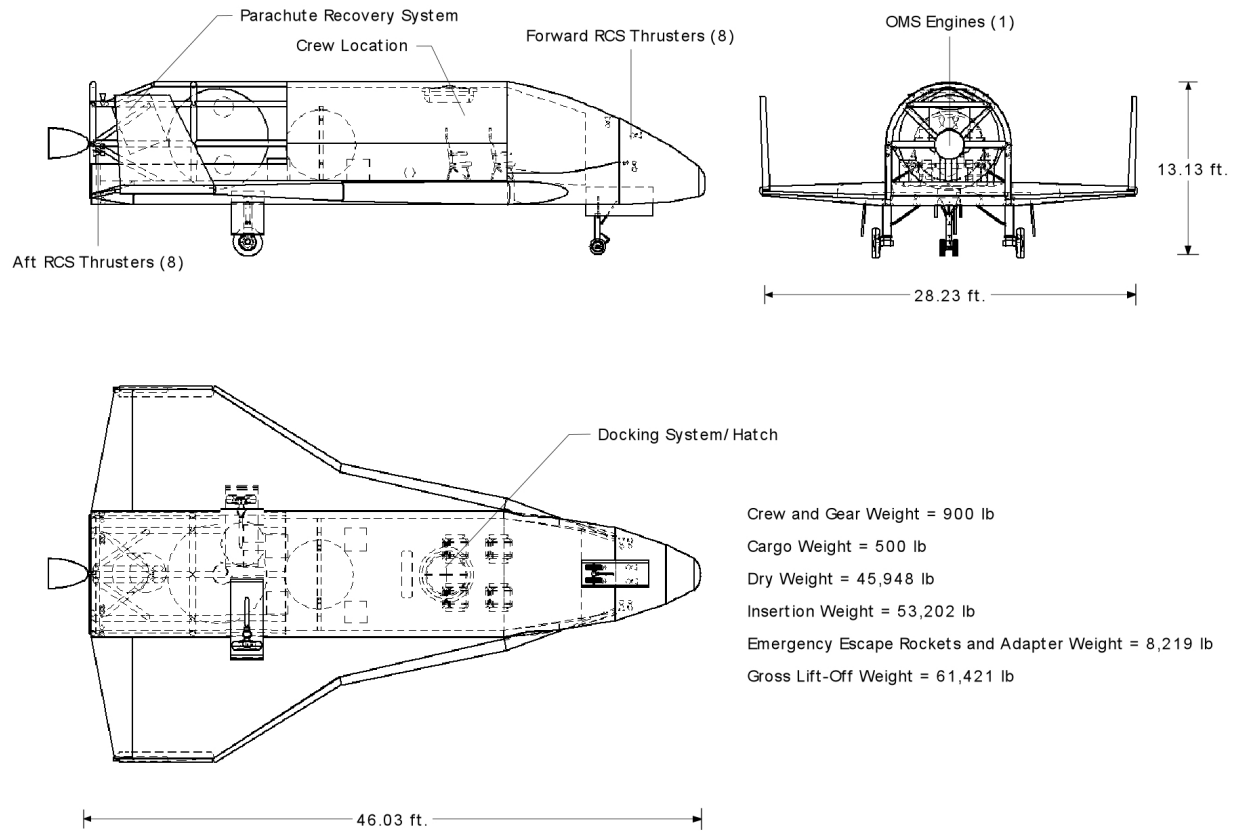


Figure D.7. Context 1 Three View: Design Approach 12 (Roll-Up)

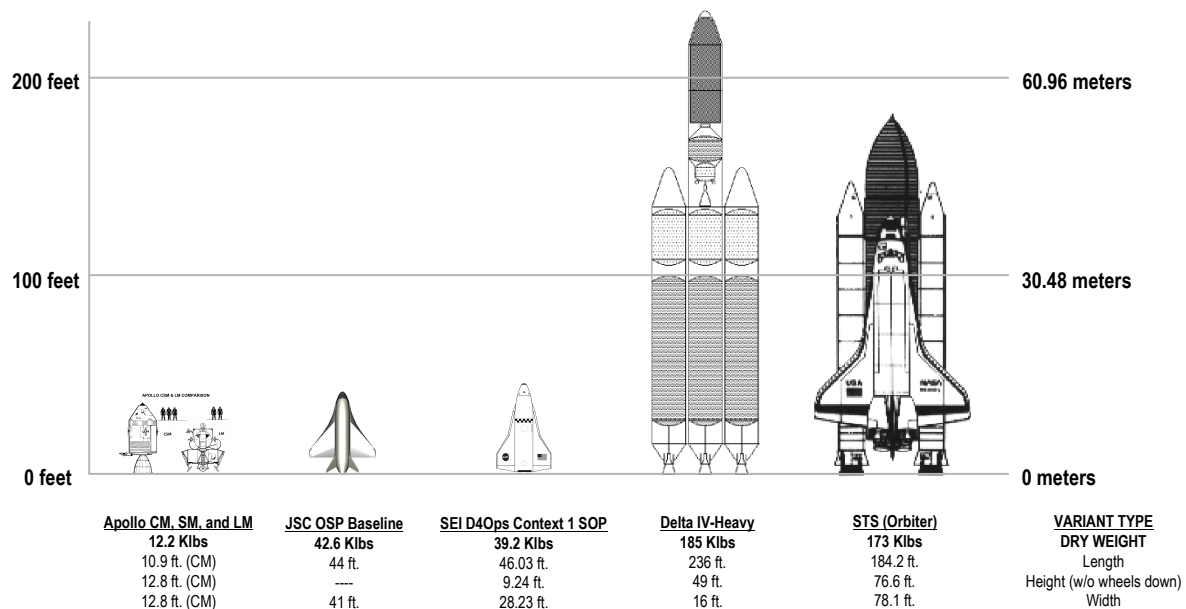
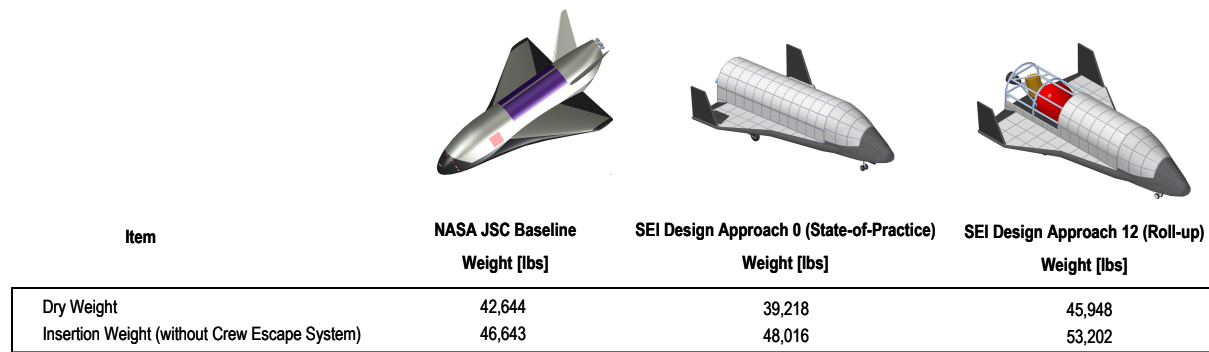
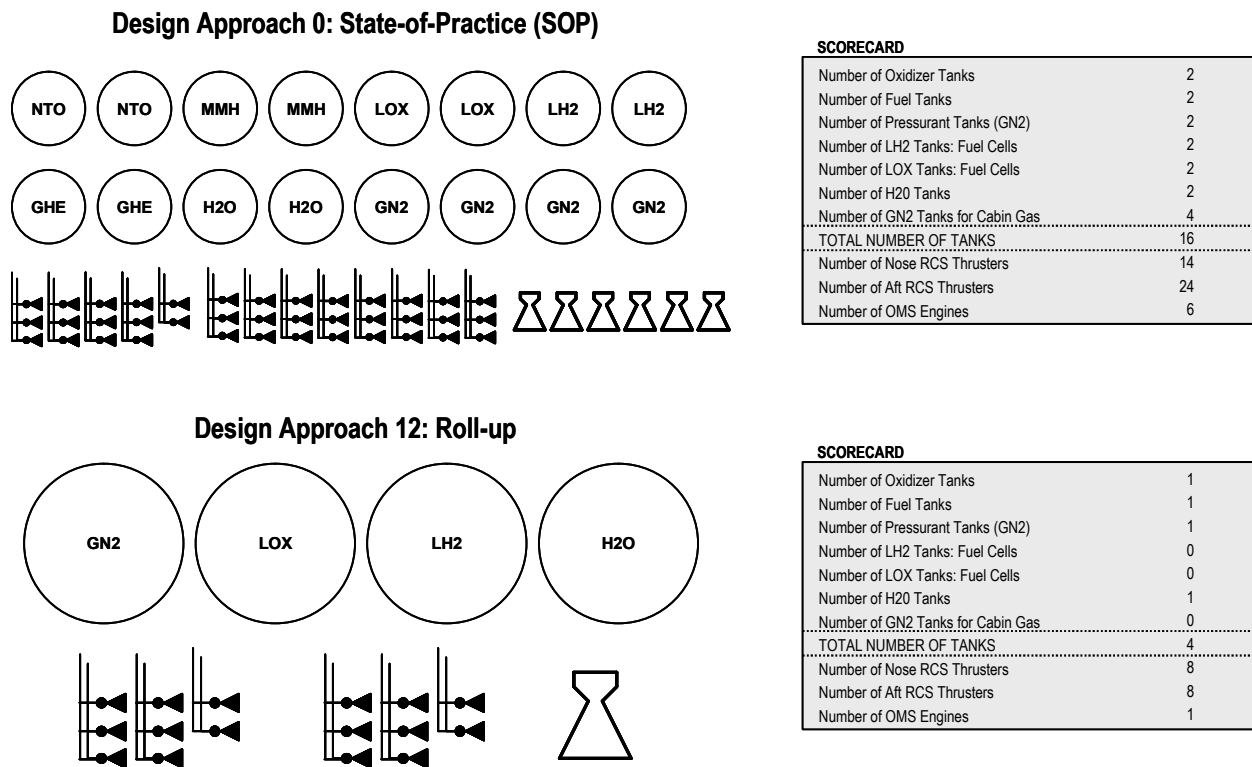


Figure D.8. D4Ops Context 1 Scale Comparison



**Figure D.9. Context 1 Comparison of NASA JSC OSP Baseline with SEI State-of-Practice (SOP) and Approach 12 (Roll-up)**

Note: NASA JSC analysis assumed 27,000 lb entry weight for vehicle with insertion weight (i.e. release from booster and discard of Crew Escape System or CES) equal to that plus 3,999 lb of assumed propellant, therefore, actual NASA JSC insertion weight (from the WBS) is more, therefore NASA JSC OSP baseline is too low on NTO/MMH propellant for desired mission. SEI estimates for Power and Electrical Conversion and Distribution (ECD) are generally lower than the JSC reference.



**Figure D.10. Context 1 Tank/Propulsion Comparison: State-of-Practice (SOP) versus Approach Rollup**

The elimination of major end items and extreme integration example considered here is used to demonstrate the direction of further design, technology, or D4Ops areas of emphasis as well as analysis, modeling and trade sensitivities and directions. Actual execution approaches may still include at least dual redundancies in these tightly integrated system/sub-system designs.

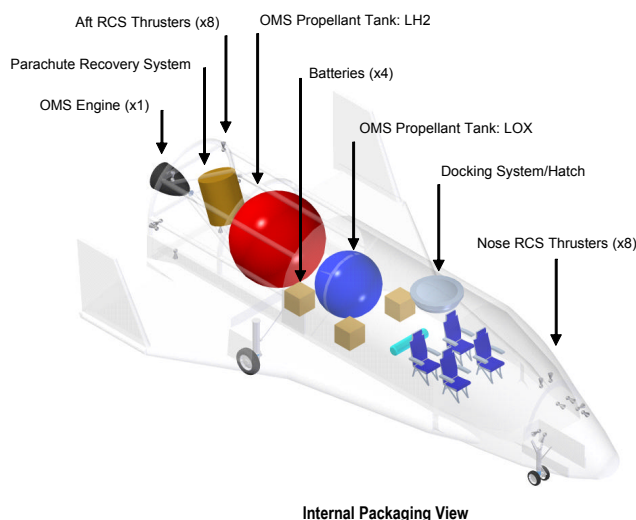


Figure D.11. D4Ops Context 1: Design Approach Nomenclature

Table D.9. D4Ops Context 1: Design Approach Weight Modeling Impacts

Approach	Weight Impact
1: Reduce Parts	Minimize tank counts (1 MMH tank, 1 N2O4 tank, 1 He tank, 1 water tank, 1 N2 tank); eliminate redundant fuel cells (1 fuel cell stack and 1 unified LOX tank and 1 LH2 reactant tank); reduce engine counts (1 OMS engine, 8 aft thrusters, 8 forward thrusters); increase current engine and tankage total weights by 15% to account for increased robustness. Reduce overall avionics weights by 25% to reflect lower redundancy.
2: Reduce Engines	Reduce to 1 OMS engine, 8 aft thrusters, 8 forward thrusters. Assume total engine weights do not change (fewer, but larger thrusters).
3: All Electric	Eliminate fuel cell stacks, reactant tankage, and reactants. Size new extended 24 VDC Li-Ion batteries for entire 5-day mission (high tech @350 W-hr/kg).
4: No Hypergols	Increase engine and thruster weights by 25%. Increase line weights by 20%. Change fuel and oxidizer densities to 4.41 and 72.1, respectively. Change O/F ratio to 5.5. Increase fuel and oxidizer tankage unit weights by 10% for extra insulation. Increase Isp to 420 sec.
5: No Hypergols/Cryogens	Increase OMS engine and thrusters weights by 10%. Change fuel and oxidizer densities to 70.5 and 88, respectively. Change O/F ratio to 5. Change Isp to 312 sec.
6: Uniform TPS	Add 40% to acreage unit weights for AETB-8 tiles. Add 100% to acreage unit weights for blankets to account for overall thickness increases.
7: Robust TPS	Reduce overall TPS weight by 100 lb for fewer access panels. Add 0.15 lb/ft <sup>2</sup> for sealing and surface treatment on all acreage weights.
8: P-IVHM	Add 100 lb to OMS propulsion for controllers and sensors. Add 100 lb to RCS propulsion for controllers and sensors. Increase baseline Avionics weights by 10%.
9: Less Aeroshell	Reduce aftbody main structure by 15%. Reduce TPS blankets weight by 15%. Eliminate base area structure completely. Add 15% weight to each of the following: RCS propulsion, OMS propulsion, ECLSS, Power, and ECD weights.
10: Common Prop./Power	Increase engine and thrusters weights by 25%. Increase line weights by 20%. Change fuel and oxidizer densities to 4.41 and 72.1, respectively. Change O/F ratio to 5.5. Increase fuel and oxidizer propellant tankage unit weights by 10%. Increase Isp to 420 sec. Eliminate Fuel Cell tanks and tankage weights (leaving 2 unified LOX, 2 unified LH2, 2 water, 2 He, 4 N2 tanks). Add volume of fuel cell reactants to propellant tanks.
11: Common Prop./Power/ECLSS	Increase engine and thrusters weights by 25%. Increase line weights by 20%. Change fuel and oxidizer densities to 4.41 and 72.1, respectively. Change O/F ratio to 5.5. Increase fuel and oxidizer propellant tank unit weights by 10%. Increase Isp to 420 sec. Eliminate Fuel Cell reactant line item and associated tankage weights. Add volume of fuel cell reactants to OMS propellant tanks. Change He pressurant tanks to N2. Increase pressurant tank unit weight by 40% for reduced efficiency of N2. Combine N2 with ECLSS by eliminating cabin N2 gas weight and N2 tankage. Add cabin N2 gas weight to propulsion pressurization system (leaving 2 unified LOX, 2 unified LH2, 2 unified N2, 2 water tanks).
12: Roll-Up	Minimize tank counts (1 LH2 tank, 1 unified LOX tank, 1 water tank, 1 unified N2 tank). Reduce to 1 OMS engine, 8 aft thrusters, 8 forward thrusters (all LOX/LH2, fewer but larger thrusters). Increase engine and thruster Level 1 weights by 45% to account for cryogenic propellants and also for more reliable hardware (fewer engines, but design for same overall reliability) and open trusswork on aftbody. Add additional 100 lb to resultant OMS and 100 lb to resultant RCS thrusters to account for extra sensors and controllers. Change fuel and oxidizer densities to 4.41 and 72.1, respectively. Change O/F ratio to 5.5. Increase Isp to 420 sec. Increase line weights by 25%. Increase fuel and oxidizer tanks weights by 25% to account for cryogenics and open trusswork aftbody. Assume Avionics weights are unchanged from baseline after accounting for less redundancy, but also extra exposure to aeroheating and extra IVHM systems. Eliminate fuel cell stacks, reactant tankage, and reactants. Size new extended 24 VDC Li-Ion b, increase TPS tile unit weights by 50% for added robustness (sealants, surface treatments) and non-optimized thickness. Increase TPS blanket unit weights by 100% (assume added robustness and uniform thickness, but less blanket area due to new open compartment structural configuration of aftbody). Add 15% to ECD and ECLSS weights to account for aeroheating exposure. Reduce aftbody main structure by 15% to eliminate some of the aeroshell. Eliminate base area completely.

**Table D.10. D4Ops Context 1: Design Approach Non-Recurring Cost Modeling Impacts**

Approach	NAFCOM Non-Recurring Cost Impact
1: Reduce Parts	The following applies equally to DDT&E and TFU complexity factors: Increase avionics complexity by 10% to account for increased monitoring of systems, increase system test hardware by 10%, in order to account for the cost of building more reliable components increase the complexity on the following CER categories by 5%: body, power, OMS, RCS
2: Reduce Engines	The following applies equally to DDT&E and TFU complexity factors: Increase system test hardware by 5%, In order to account for the cost of building more reliable components increase the complexity on the following CER categories by 5%: OMS, RCS
3: All Electric	The following applies to TFU complexity factors: decrease power complexity by 20%
4: No Hypergols	The following applies equally to DDT&E and TFU complexity factors: increase OMS/RCS complexity by 25%
5: No Hypergols/Cryogens	The following applies equally to DDT&E and TFU complexity factors: Increase OMS/RCS complexity by 15%
6: Uniform TPS	The following applies equally to DDT&E and TFU complexity factors: reduce TPS complexity by 20%
7: Robust TPS	The following applies equally to DDT&E and TFU complexity factors: Increase TPS complexity by 25%, Increase system test hardware by 5%
8: P-IVHM	Increase avionics complexity by 25%, increase OMS/RCS complexity by 5%, increase system test hardware by 5%
9: Less Aeroshell	The following applies equally to DDT&E and TFU complexity factors: Add 20% to System Test Hardware, reduce by 10% Integration, Assembly, & Checkout (IACO), Add 2% to Body complexity, Add 3% to the following: OMS, RCS, Electrical Conversion, Power, and Environmental Control
10: Common Prop./Power	The following applies equally to DDT&E and TFU complexity factors: Add 5% to System Test Hardware; Increase the complexity on the following CER categories by 5%: power
11: Common Prop./Power/ECLSS	The following applies equally to DDT&E and TFU complexity factors: Add 10% to System Test Hardware; Increase the complexity on the following CER categories by 7%: body, power, OMS, RCS, environmental control
12: Roll-Up	The following applies equally to DDT&E and TFU complexity factors: System Test hardware by 53%, Avionics by 30%, Body by 7%, Power by 15%, OMS by 19%, RCS by 19%, Electrical by 5%, TPS by 10%, Environmental Control by 3%, and IACO by -10%

**Table D.11. D4Ops Context 1: Design Approach Safety Modeling Impacts**

Approach	GTSafety-II Safety Impact
1: Reduce Parts	Ground Handling Complexity feature increases to 3.4, Propellant Loading Process feature increases to 3.2, Assume total propellant feed and storage end-to-end failure rates stay the same
2: Reduce Engines	Ground Handling Complexity feature increased to 3.3, Assume total propellant feed and storage end-to-end failure rates stay the same
3: All Electric	Ground Handling Complexity feature increased to 3.3, Volatile Fluids feature increased to 3.1, Propellant Loading Process feature to 3.1, Decrease electrical system failure rate by 20%, propellant feed system failures reduced by 20%
4: No Hypergols	Ground Handling Complexity increased to 3.3, Safety Factors feature increased to 3.2, Toxic Fluids feature increased to 3.5, Propellant Loading Process feature increased to 3.1
5: No Hypergols/Cryogens	Ground Handling Complexity increased to 3.3, Safety Factors feature increased to 3.2, Toxic Fluids feature increased to 3.5, Propellant Loading Process feature increased to 3.2, Volatile Fluids feature increased to 3.1
6: Uniform TPS	Ground Handling Complexity increased to 3.3, no effect on overall end-to-end TPS system failure, Catastrophic TPS Failure/Total TPS Failures decrease to 0.08
7: Robust TPS	Decrease TPS failure rate to 1 in 6000, Catastrophic TPS Failure/Total TPS Failures decrease to 0.07, Ground Handling Complexity feature decreased to 3.1
8: P-IVHM	Increase IVHM feature to 3.3, decrease Single Engine Shutdown Rate for Rocket (flights) to 1 in 10000
9: Less Aeroshell	Assume total end-to-end failure rates of subsystems stay the same, Ground Handling Complexity feature increased to 3.2
10: Common Prop./Power	Assume total end-to-end failure rates of subsystems stay the same, Ground Handling Complexity feature increased to 3.3, Propellant Loading Process feature increased to 3.1, Volatile Fluids feature increased to 3.1
11: Common Prop./Power/ECLSS	Assume total end-to-end failure rates of subsystems stay the same, Ground Handling Complexity feature increased to 3.4, Propellant Loading Process feature increased to 3.3, Volatile Fluids feature increased to 3.1
12: Roll-Up	Toxic Fluids feature increased to 3.5, Safety Factors increased to 3.2, Decrease electrical system failure rate by 20%, propellant feed system failures reduced by 20%, Increase IVHM feature to 3.3, decrease Single Engine Shutdown Rate for Rocket (flights) to 1 in 10000, decrease TPS failure rate to 1 in 6000, Volatile Fluids feature increased to 3.2, Catastrophic TPS Failure/Total TPS Failures decrease to 0.07, Propellant Loading Process feature increases to 3.6, Ground Handling Complexity feature increased to 4.5

Table D.12. D4Ops Context 1: Design Approach Operations Modeling Impacts

Approach	AATe Operations Impact
1: Reduce Parts	Dry Weight = 55.034 klbs, Question 9: 3, Question 1.2: C1 check and C2 unchecked Slightly less but very complex than STS, Less than 10 tanks
2: Reduce Engines	Dry Weight = 55.665 klbs, Question 9: 3 Slightly less but very complex than STS
3: All Electric	Dry Weight = 55.243 klbs, Question 9: 3, Question 12.2: 16/20 unchecked Slightly less but very complex than STS, No LOX(propellant grade)/LH2
4: No Hypergols	Dry Weight = 57.738 klbs, Question 4: 3, Question 9: 3, Question 12.2: 13/15 unchecked [Added 20% additional qualitative margin onto Total GSE/FAC cost] Slightly less but very complex than STS, Requires no use of pollutive or toxic materials on the flight vehicle but may use in other operations, no hypergolic propellants
5: No Hypergols/Cryogens	Dry Weight = 55.403 klbs, Question 4: 3, Question 9: 3, Question 11: 3, Question 12.2: 13/15/16/20 unchecked, Question 12.2: 6/10 check [Added 20% additional qualitative margin onto Total GSC/FAC cost] Slightly less but very complex than STS, No pollutive or toxics on flight vehicle but in other operations, Uses fewer toxic fluids, No hypergolic propellants, No LOX(propellant grade)/LH2, Use H2O2/Ethanol
6: Uniform TPS	Dry Weight = 58.313 klbs, Question 9: 2 Slightly less but complex than STS
7: Robust TPS	Dry Weight = 56.010 klbs, Question 9: 3, Question 12.2: 2 unchecked Slightly less but very complex than STS, No DMES / Waterproofing Agent
8: P-IVHM	Dry Weight = 56.426 klbs, Question 1.2: D1 check, Question 6: 3, Question 15: 3 [Added 20% additional qualitative margin onto Total GSE/FAC cost] Shared hardware/software between avionics/health management, Mix of COTS & custom components with low TRL, Limited intrusive sensors requiring no hands-on or ground support
9: Less Aeroshell	Dry Weight = 56.953 klbs, Question 5: 3, Question 16: 3, Question 17: 3 Aeroshell, More maintainable leak checking, Fewer closed compartments
10: Common Prop./Power	Dry Weight = 56.515 klbs, Question 9: 3, Question 11: 3, Question 1.2: B2/B3 check Slightly less but very complex than STS, No pollutive or toxics on flight vehicle but in other operations, OMS/RCS/Power feed off same tanks
11: Common Prop./Power/ECLSS	Dry Weight = 58.570 klbs, Question 9: 3, Question 11: 3, Question 13: 4, Question 1.2: B2/B3/C1 check and C2 unchecked Slightly less but very complex than STS, No pollutive or toxics on flight vehicle but in other operations, reduced gases on stages, OMS/RCS/Power feed off same tanks, Less than 10 tanks
12: Roll-Up	Dry Weight = 61.420 klbs, Question 1.2: B2/B3/C1/D1 check and C2 unchecked, Question 9: 2, Question 11: 3, Question 12.2: 2/13/15 unchecked, Question 13: 4, Question 15: 3, Question 16: 3, Question 17: 3 [Added 5% additional qualitative margin onto Total GSE/FAC cost] Slightly less but complex than STS, OMS/RCS/Power feed off same tanks, Less than 10 tanks, Shared hardware/software between avionics/health management, No pollutive or toxics on flight vehicle but in other operations, No DMES / Waterproofing Agent, No hypergolic propellants, reduced gases on stages, Limited intrusive sensors requiring no hands-on or ground support, More maintainable leak checking, Fewer closed compartments

Table D.13. D4Ops Context 1 Metrics Summary: State-of-Practice (SOP)

Weight Item	Weight [lbs]	% of Dry Weight
Wings	5,709	14.6%
Vertical Tails/Winglets	405	1.0%
Main Body Structure	9,690	24.7%
Thermal Protection	2,685	6.8%
Landing Gear	1,837	4.7%
Main Propulsion	0	0.0%
RCS Propulsion	580	1.5%
OMS Propulsion	1,562	4.0%
Primary Power	2,102	5.4%
Electrical Conversion and Distribution	2,432	6.2%
Hydraulic Systems	0	0.0%
Surface Control Actuation	1,283	3.3%
Avionics	1,900	4.8%
Environmental Control	2,701	6.9%
Personnel Equipment	1,218	3.1%
Growth Margin	5,115	13.0%
<b>Dry Weight</b>	<b>39,218</b>	<b>100.0%</b>
Crew and Gear	900	
Payload Provisions	0	
Cargo (up and down)	500	
Residual Propellants	68	
Reserve Propellants	136	
<b>Landed Weight</b>	<b>40,822</b>	
Entry Propellants	102	
<b>Entry Weight</b>	<b>40,924</b>	
OMS/RCS Propellants (consumed on-orbit)	6,699	
Cargo Discharged but not Returned	0	
Main Ascent Reserves	0	
Other Inflight Losses and Vents	393	
<b>Insertion Weight</b>	<b>48,016</b>	
Main Engine Ascent Propellants	0	
Emergency Escape Rockets & Adapter	7,649	
<b>Gross Liftoff Weight (with CES)</b>	<b>55,665</b>	

## SCORECARD

Number of Oxidizer Tanks	2
Number of Fuel Tanks	2
Number of Pressurant Tanks	2
Number of LH2 Tanks: Fuel Cells	2
Number of LOX Tanks: Fuel Cells	2
Number of H2O Tanks	2
Number of GN2 Tanks for Cabin Gas	4
<b>TOTAL NUMBER OF TANKS</b>	<b>16</b>
Number of Nose RCS Thrusters	14
Number of Aft RCS Thrusters	24
Number of OMS Engines	6

## SUMMARY METRICS (in FY2003 unless otherwise noted)

<b>NON-RECURRING AND LIFE CYCLE COST</b>	
DDT&E Cost [\$M]	\$3,443 M
TFU Cost [\$M]	\$703 M
Life Cycle Cost [\$M] at 4 and 16 Flights/Year	\$21,036 M / \$28,574 M
Cost Per Flight [\$M/Flight] at 4 and 16 Flights/Year	\$309.35 M / \$105.05 M
<b>SAFETY</b>	
Loss of Mission (LOM) MFBF / Reliability	1 in 518 Flights / 0.99807
Loss of Vehicle (LOV) MFBF / Reliability	1 in 1,930 Flights / 0.99948
Loss of Crew (LOC) MFBF / Reliability	1 in 3,927 Flights / 0.99975
Casualty Rate [casualties per year]	4.32E-03
<b>OPERATIONS</b>	
Fixed Operational: Annual Operations Costs [\$M]	\$527.7 M
GSE/Facility Cost: Annual Operations Costs [\$M]	\$147.9 M
GSE/Facility Cost: Non-Annualized Cost [\$M]	\$1,720.3 M
Variable Costs per Flight [\$M]	\$32.8 M
Total Cycle Time	55.20 days

Table D.14. D4Ops Context 1: Metrics Comparison

Item	Dry Weight [lbs]	Gross Liftoff Weight (with CES) [lbs]	DDT&E Cost [FY2003\$M]	TFU Cost [FY2003\$M]	Loss of Vehicle (LOV) [Reliability]	GSE/Facility Costs (non- annualized) [FY2003\$M]	Ops Costs per Flight (variable @ 4 flts/yr) [FY2003\$M]	Total Cycle Time [Days]	Total Number of Tanks [Number]
Best Answer (Approaches 1-12)									
Worst Answer (Approaches 1-12)									
State of Practice (SOP)	39,218	55,665	\$3,443	\$703	0.99948	\$1,720.3	\$32.8	55.20	16
Approach 1 (Reduce Parts)	38,732	55,034	\$3,671	\$719	0.99952	\$1,577.6	\$30.1	51.50	7
Approach 2 (Reduce Engines)	39,218	55,665	\$3,531	\$711	0.99952	\$1,600.9	\$30.9	51.90	16
Approach 3 (All Electric)	39,275	55,243	\$3,434	\$695	0.99953	\$1,573.6	\$30.4	51.10	14
Approach 4 (No Hypergols)	42,613	57,738	\$3,926	\$841	0.99959	\$1,657.8	\$27.5	45.50	16
Approach 5 (No Hypergols/Cryogens)	39,057	55,403	\$3,514	\$722	0.99959	\$1,570.7	\$25.7	44.00	16
Approach 6 (Uniform TPS)	41,255	58,313	\$3,474	\$713	0.99948	\$1,439.2	\$28.3	47.80	16
Approach 7 (Robust TPS)	39,483	56,010	\$3,638	\$728	0.99943	\$1,540.9	\$29.9	50.20	16
Approach 8 (P-IVHM)	39,804	56,426	\$3,657	\$727	0.99969	\$1,807.9	\$28.1	48.70	16
Approach 9 (Less Aeroshell)	40,209	56,953	\$3,799	\$728	0.99948	\$1,435.5	\$28.0	47.00	16
Approach 10 (Common Prop./Power)	41,228	56,515	\$3,734	\$774	0.99948	\$1,396.7	\$25.8	47.50	12
Approach 11 (Common Prop./Power/ECLSS)	42,876	58,570	\$4,030	\$834	0.99948	\$1,464.3	\$27.2	49.20	8
Approach 12 (Roll-up)	45,948	61,420	\$5,340	\$956	0.99979	\$934.0	\$17.6	32.30	4
<b>Difference from State of Practice (SOP)</b>									
State of Practice (SOP)	0.0%	0.0%	0.0%	0.0%	0.000%	0.0%	0.0%	0.0%	0.0%
Approach 1 (Reduce Parts)	-1.2%	-1.1%	6.6%	2.2%	0.004%	-8.3%	-8.1%	-6.7%	-56.3%
Approach 2 (Reduce Engines)	0.0%	0.0%	2.6%	1.1%	0.004%	-6.9%	-5.8%	-6.0%	0.0%
Approach 3 (All Electric)	0.1%	-0.8%	-0.3%	-1.2%	0.004%	-8.5%	-7.1%	-7.4%	-12.5%
Approach 4 (No Hypergols)	8.7%	3.7%	14.0%	19.7%	0.011%	-3.6%	-16.2%	-17.6%	0.0%
Approach 5 (No Hypergols/Cryogens)	-0.4%	-0.5%	2.0%	2.7%	0.011%	-8.7%	-21.8%	-20.3%	0.0%
Approach 6 (Uniform TPS)	5.2%	4.8%	0.9%	1.5%	0.000%	-16.3%	-13.6%	-13.4%	0.0%
Approach 7 (Robust TPS)	0.7%	0.6%	5.7%	3.6%	-0.005%	-10.4%	-8.8%	-9.1%	0.0%
Approach 8 (P-IVHM)	1.5%	1.4%	6.2%	3.4%	0.020%	5.1%	-14.3%	-11.8%	0.0%
Approach 9 (Less Aeroshell)	2.5%	2.3%	10.3%	3.5%	0.000%	-16.6%	-14.6%	-14.9%	0.0%
Approach 10 (Common Prop./Power)	5.1%	1.5%	8.4%	10.0%	0.000%	-18.8%	-21.4%	-13.9%	-25.0%
Approach 11 (Common Prop./Power/ECLSS)	9.3%	5.2%	17.0%	18.6%	0.000%	-14.9%	-16.9%	-10.9%	-50.0%
Approach 12 (Roll-up)	17.2%	10.3%	55.1%	36.0%	0.030%	-45.7%	-46.4%	-41.5%	-75.0%

Table D.15. D4Ops Context 1: Life Cycle Cost (LCC) Metrics Comparison

Item	Life Cycle Cost at 4 Flights/Year [FY2003\$M]	Life Cycle Cost at 16 Flights/Year [FY2003\$M]	Life Cycle Cost Per Flight at 4 Flights/Year [FY2003\$M/Flight]	Life Cycle Cost Per Flight at 16 Flights/Year [FY2003\$M/Flight]
Best Answer (Approaches 1-12)				
Worst Answer (Approaches 1-12)				
State of Practice (SOP)	\$21,036.0	\$28,574.0	\$309.4	\$105.1
Approach 1 (Reduce Parts)	\$19,994.0	\$26,978.0	\$294.0	\$99.2
Approach 2 (Reduce Engines)	\$20,213.0	\$27,349.0	\$297.2	\$100.6
Approach 3 (All Electric)	\$19,873.0	\$26,906.0	\$292.3	\$98.9
Approach 4 (No Hypergols)	\$19,477.0	\$25,995.0	\$286.4	\$95.6
Approach 5 (No Hypergols/Cryogens)	\$17,894.0	\$23,930.0	\$263.1	\$88.0
Approach 6 (Uniform TPS)	\$18,893.0	\$25,488.0	\$277.8	\$93.7
Approach 7 (Robust TPS)	\$19,899.0	\$26,846.0	\$292.6	\$98.7
Approach 8 (P-IVHM)	\$19,377.0	\$25,898.0	\$284.4	\$95.2
Approach 9 (Less Aeroshell)	\$19,047.0	\$25,586.0	\$280.1	\$94.1
Approach 10 (Common Prop./Power)	\$18,024.0	\$24,122.0	\$265.0	\$88.7
Approach 11 (Common Prop./Power/ECLSS)	\$19,117.0	\$25,583.0	\$281.0	\$94.1
Approach 12 (Roll-up)	\$15,961.0	\$20,466.0	\$234.7	\$75.2
<b>Difference from State of Practice (SOP)</b>				
State of Practice (SOP)	0.0%	0.0%	0.0%	0.0%
Approach 1 (Reduce Parts)	-5.0%	-5.6%	-5.0%	-5.6%
Approach 2 (Reduce Engines)	-3.9%	-4.3%	-3.9%	-4.3%
Approach 3 (All Electric)	-5.5%	-5.8%	-5.5%	-5.8%
Approach 4 (No Hypergols)	-7.4%	-9.0%	-7.4%	-9.0%
Approach 5 (No Hypergols/Cryogens)	-14.9%	-16.3%	-14.9%	-16.2%
Approach 6 (Uniform TPS)	-10.2%	-10.8%	-10.2%	-10.8%
Approach 7 (Robust TPS)	-5.4%	-6.0%	-5.4%	-6.0%
Approach 8 (P-IVHM)	-7.9%	-9.4%	-8.1%	-9.4%
Approach 9 (Less Aeroshell)	-9.5%	-10.5%	-9.5%	-10.5%
Approach 10 (Common Prop./Power)	-14.3%	-15.6%	-14.3%	-15.6%
Approach 11 (Common Prop./Power/ECLSS)	-9.1%	-10.5%	-9.2%	-10.5%
Approach 12 (Roll-up)	-24.1%	-28.4%	-24.1%	-28.4%

Table D.16. D4Ops Context 1: Metrics Comparison (Normalized)

Item	Dry Weight [lbs]	Gross Liftoff Weight (with CES) [lbs]	DDT&E Cost [FY2003\$M]	TFU Cost [FY2003\$M]	Loss of Vehicle (LOV) [Reliability]	GSE/Facility Costs (non- annualized) [FY2003\$M]	Ops Costs per Flight (variable @ 4 flts/yr) [FY2003\$M]	Total Cycle Time [Days]	Total Number of Tanks [Number]
Best Answer (Approaches 1-12)									
Worst Answer (Approaches 1-12)									
State of Practice (SOP)	100	100	100	100	100.000	100	100	100	16
Approach 1 (Reduce Parts)	99	99	107	102	100.004	92	92	93	7
Approach 2 (Reduce Engines)	100	100	103	101	100.004	93	94	94	16
Approach 3 (All Electric)	100	99	100	99	100.004	91	93	93	14
Approach 4 (No Hypergols)	109	104	114	120	100.011	96	84	82	16
Approach 5 (No Hypergols/Cryogens)	100	100	102	103	100.011	91	78	80	16
Approach 6 (Uniform TPS)	105	105	101	101	100.000	84	86	87	16
Approach 7 (Robust TPS)	101	101	106	104	99.995	90	91	91	16
Approach 8 (P-IVHM)	101	101	106	103	100.020	105	86	88	16
Approach 9 (Less Aeroshell)	103	102	110	104	100.000	83	85	85	16
Approach 10 (Common Prop./Power)	105	102	108	110	100.000	81	79	86	12
Approach 11 (Common Prop./Power/ECLSS)	109	105	117	119	100.000	85	83	89	8
Approach 12 (Roll-up)	117	110	155	136	100.030	54	54	59	4

Table D.17. D4Ops Context 1: Life Cycle Cost (LCC) Metrics Comparison (Normalized)

Item	Life Cycle Cost at 4 Flights/Year [FY2003\$M]	Life Cycle Cost at 16 Flights/Year [FY2003\$M]	Life Cycle Cost Per Flight at 4 Flights/Year [FY2003\$/Flight]	Life Cycle Cost Per Flight at 16 Flights/Year [FY2003\$/Flight]
Best Answer (Approaches 1-12)				
Worst Answer (Approaches 1-12)				
State of Practice (SOP)	100	100	100	100
Approach 1 (Reduce Parts)	95	94	95	94
Approach 2 (Reduce Engines)	93	93	96	96
Approach 3 (All Electric)	94	94	94	94
Approach 4 (No Hypergols)	93	91	93	91
Approach 5 (No Hypergols/Cryogens)	85	84	85	84
Approach 6 (Uniform TPS)	90	89	90	89
Approach 7 (Robust TPS)	95	94	95	94
Approach 8 (P-IVHM)	92	91	92	91
Approach 9 (Less Aeroshell)	91	90	91	90
Approach 10 (Common Prop./Power)	86	84	86	84
Approach 11 (Common Prop./Power/ECLSS)	91	90	91	90
Approach 12 (Roll-up)	76	72	76	72

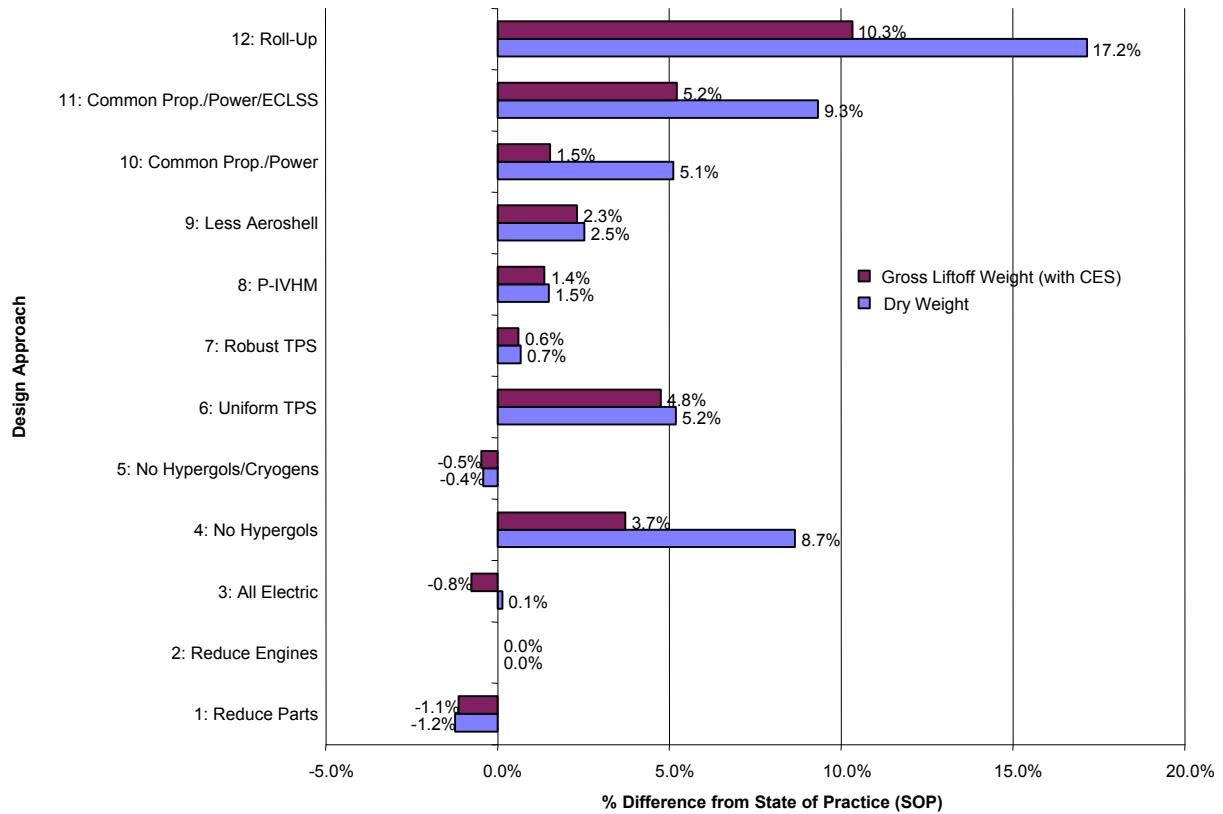


Figure D.12. D4Ops Context 1: Weight Metric Comparison to SOP

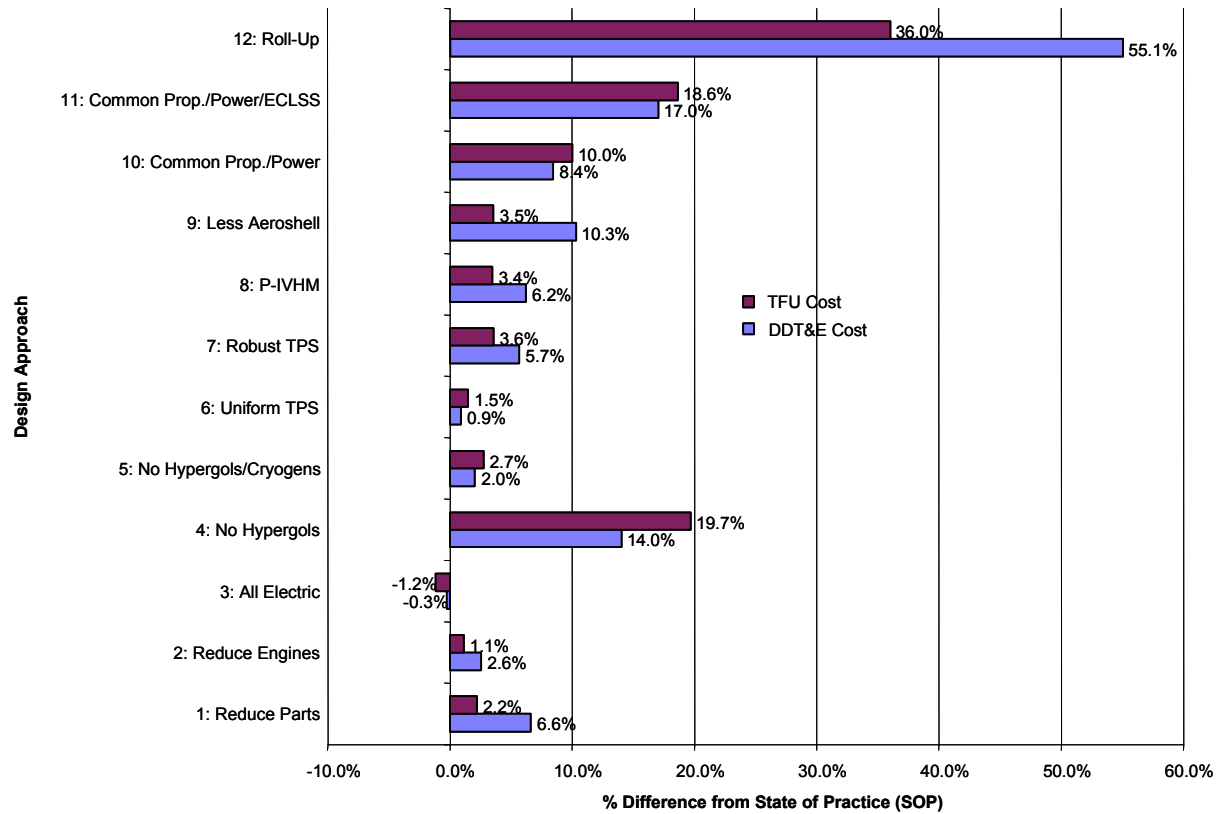


Figure D.13. D4Ops Context 1: Non-Recurring Cost Metric Comparison to SOP

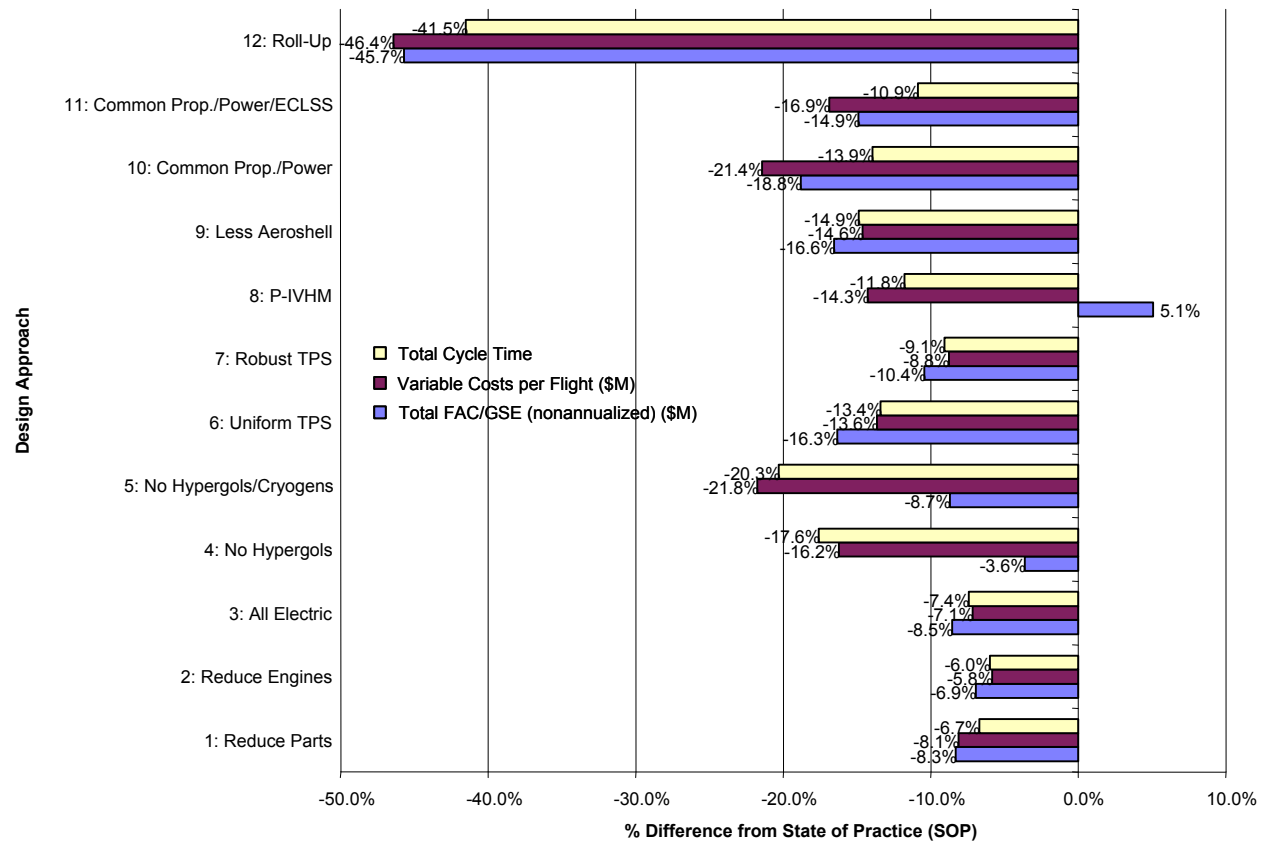


Figure D.14. D4Ops Context 1: Operations Metric Comparison to SOP

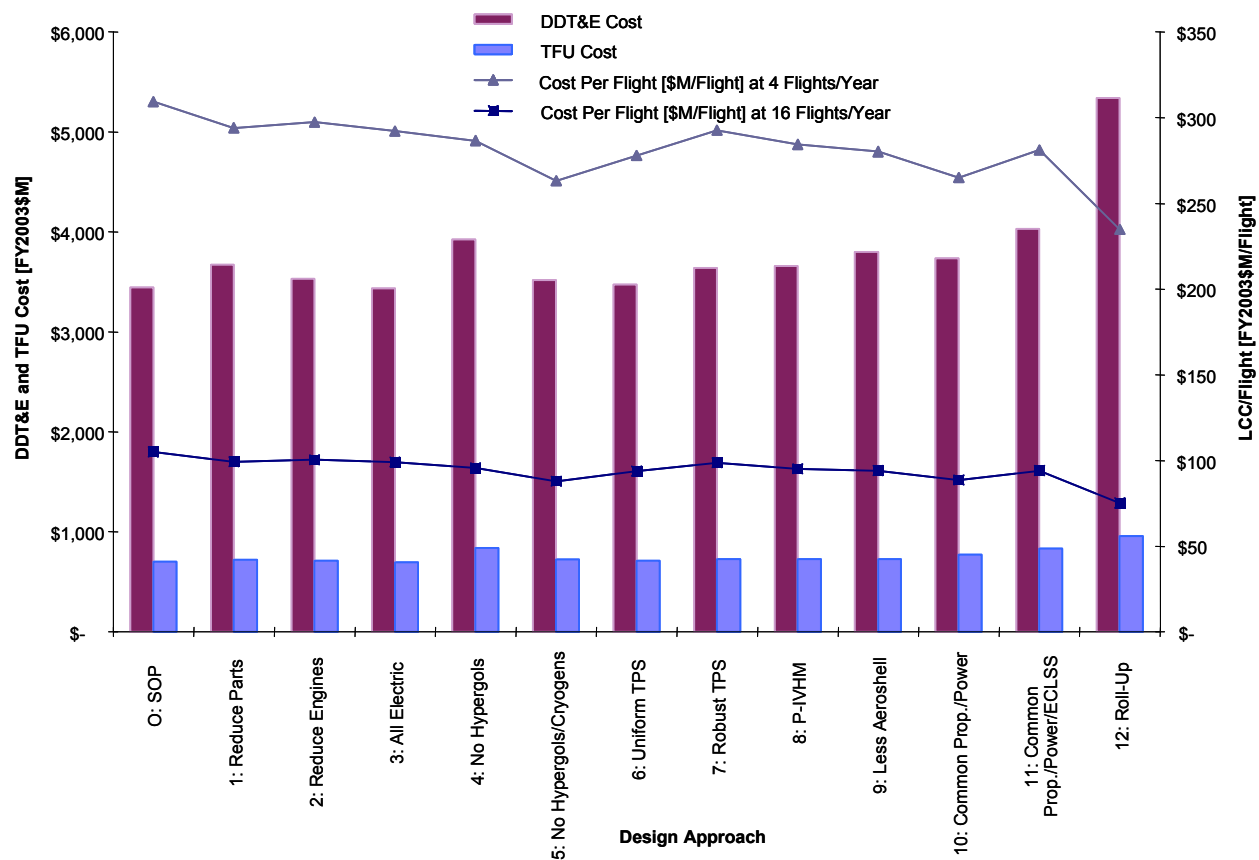


Figure D.15. D4Ops Context 1: Life Cycle Cost Comparison

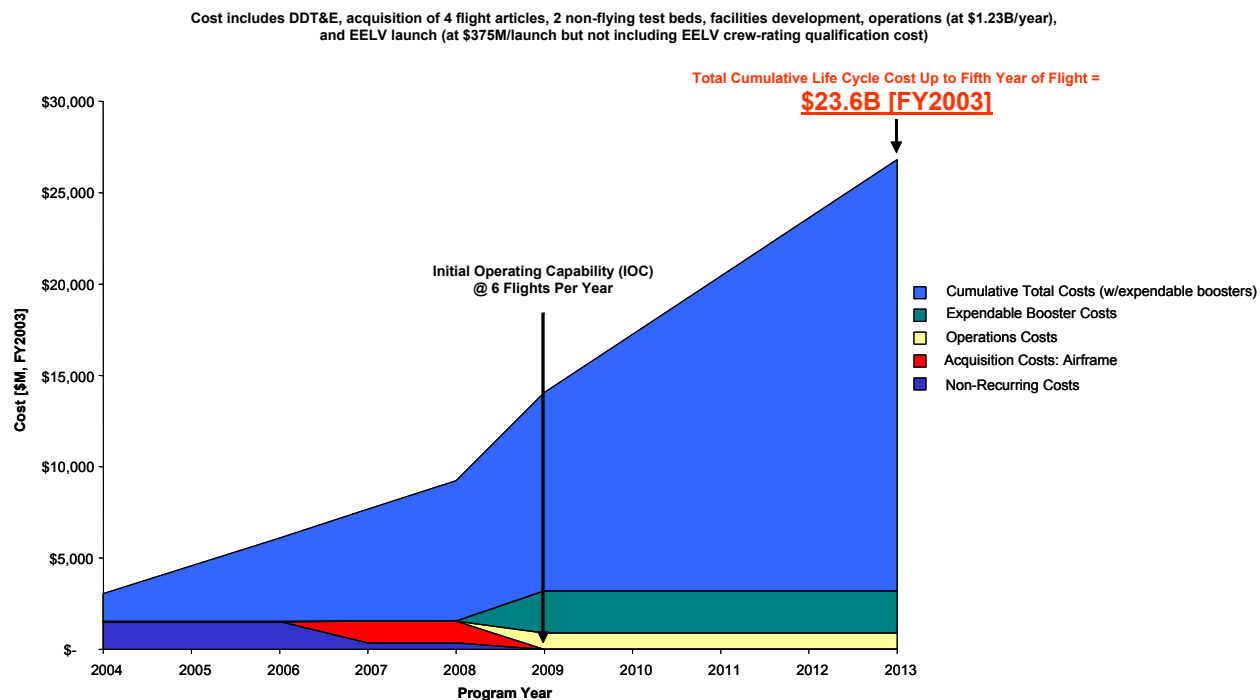


Figure D.16. D4Ops Context 1 State-of-Practice (SOP): Initial Program Cost

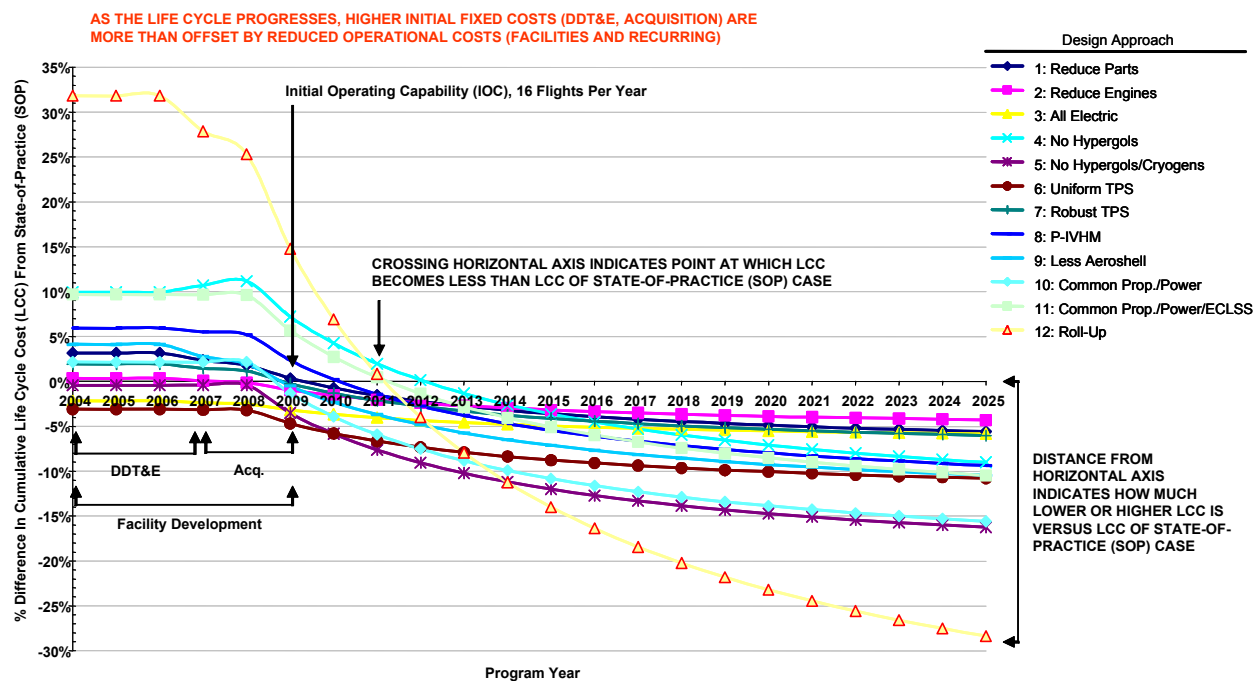


Figure D.17. D4Ops Context 1: Cumulative Life Cycle Cost Comparison to SOP

Table D.18. D4Ops Context 1: Design Approach Operations Modeling Impacts

Overall Evaluation Criteria (OEC) Components [PREFERENCE]	Weighting Scenarios									
	Even	Weight	Non-Recur. Cost	Cycle Time/ Var. Cost	Safety	Ops Cost	Life Cycle Cost	Cycle Time and Safety	DDT&E and GSE	Cycle Time
Dry Weight [MINIMIZE]	11%	43%	2%	2%	2%	2%	2%	2%	2%	2%
Gross Liftoff Weight (with CES) [MINIMIZE]	11%	43%	2%	2%	2%	2%	2%	2%	2%	2%
DDT&E Cost [MINIMIZE]	11%	2%	86%	2%	2%	2%	2%	2%	43%	2%
TFU Cost [MINIMIZE]	11%	2%	2%	2%	2%	2%	2%	2%	2%	2%
LOV Reliability [MAXIMIZE]	11%	2%	2%	2%	84%	2%	2%	43%	2%	2%
GSE/Facility: Non-Annualized (\$M) [MINIMIZE]	11%	2%	2%	2%	2%	43%	2%	2%	43%	2%
Variable Costs per Flight (\$M) [MINIMIZE]	11%	2%	2%	43%	2%	43%	2%	2%	2%	2%
Total Cycle Time (days) [MINIMIZE]	11%	2%	2%	43%	2%	2%	2%	43%	2%	84%
Life Cycle Cost [\$M] at 4 Flights/Year [MINIMIZE]	11%	2%	2%	2%	2%	2%	84%	2%	2%	2%

**Overall Evaluation Criterion (OEC)** serves as proxy for the needs of the customer, OEC can be decomposed into both qualitative and quantitative measures of fitness, a formulation of Multi-Attribute Decision Making (MADM) known as **Technique For Order Preference By Similarity To Ideal Solution (TOPSIS)** can be used to order the alternatives in the Pugh Evaluation Matrix (PEM) in terms of those that maximize the OEC

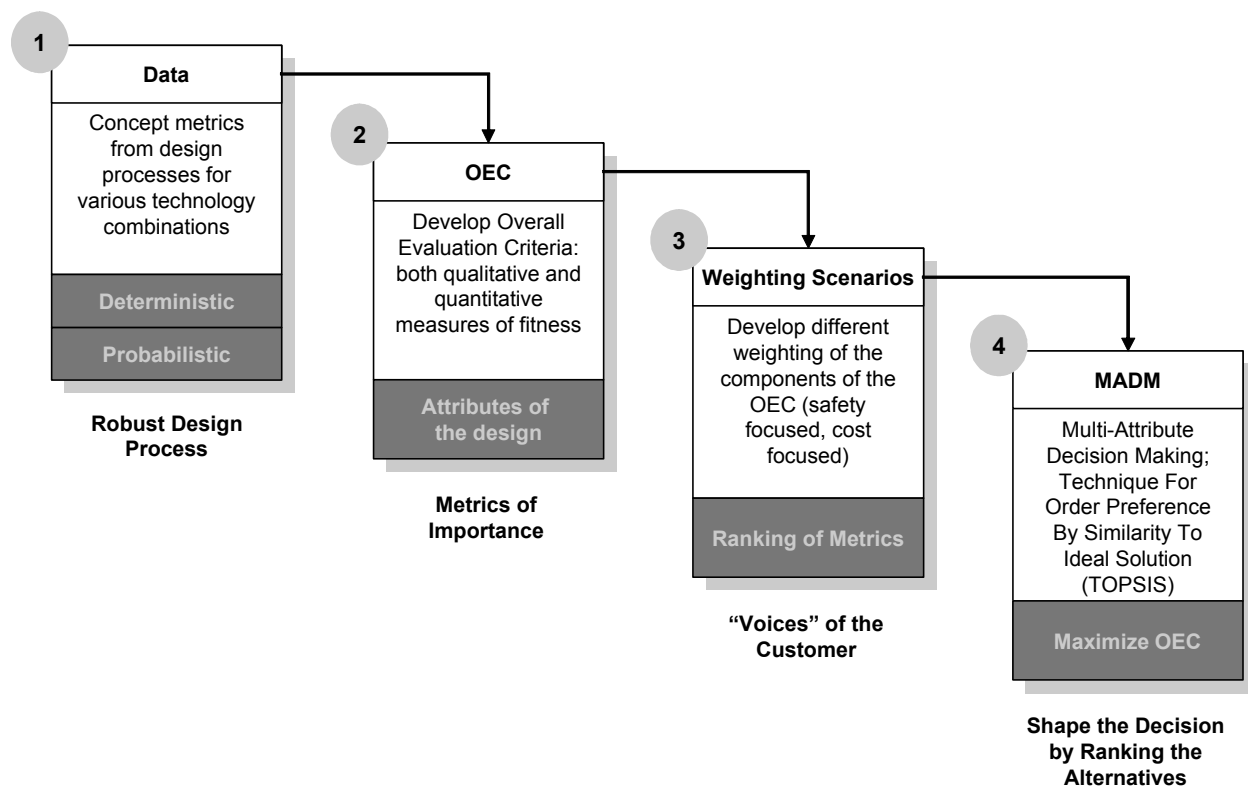


Figure D.18. Decision Making Process

Table D.19. D4Ops Context 1: Rank Across Weighting Scenarios

Design Approach	Median of Ranks	Standard Deviation of Ranks	Rank Across Weighting Scenarios [1=best]									
			Even	Weight	Non-Recur. Cost	Cycle Time/ Var. Cost	Safety	Ops Cost	Life Cycle Costs	Cycle Time and Safety	DDT&E and GSE	Cycle Time
1: Reduce Parts	9.0	2.7	8	2	7	10	8	9	11	11	9	11
2: Reduce Engines	10.0	3.2	9	4	4	12	9	11	12	12	8	12
3: All Electric	7.5	3.5	6	3	1	11	6	10	9	10	4	10
4: No Hypergols	9.0	3.6	12	10	10	4	12	8	8	3	11	3
5: No Hypergols/Cryogens	2.0	1.6	2	1	3	2	2	6	2	2	5	2
6: Uniform TPS	4.5	2.3	4	9	2	7	4	5	4	6	1	6
7: Robust TPS	7.0	1.8	7	5	5	9	7	7	10	9	6	9
8: P-IVHM	7.5	2.3	10	6	6	8	10	12	7	7	12	7
9: Less Aeroshell	5.0	1.8	5	7	9	5	5	3	5	4	3	4
10: Common Prop./Power	3.0	2.3	3	8	8	3	3	2	3	5	2	5
11: Common Prop./Power/ECLSS	9.0	2.6	11	11	11	6	11	4	6	8	10	8
12: Roll-Up	1.0	4.7	1	12	12	1	1	1	1	1	7	1

Table D.20. D4Ops Context 1: Final Rank Across Selected Weighting Scenarios

Rank [1=best]	Even Across 9 FOMs	Weight	Cycle Time	Life Cycle Costs
1	12: Roll-Up	5: No Hypergols/Cryogens	12: Roll-Up	12: Roll-Up
2	5: No Hypergols/Cryogens	1: Reduce Parts	5: No Hypergols/Cryogens	5: No Hypergols/Cryogens
3	10: Common Prop./Power	3: All Electric	4: No Hypergols	10: Common Prop./Power
4	6: Uniform TPS	2: Reduce Engines	9: Less Aeroshell	6: Uniform TPS
5	9: Less Aeroshell	7: Robust TPS	10: Common Prop./Power	9: Less Aeroshell
6	3: All Electric	8: P-IVHM	6: Uniform TPS	11: Common Prop./Power/ECLSS
7	7: Robust TPS	9: Less Aeroshell	8: P-IVHM	8: P-IVHM
8	1: Reduce Parts	10: Common Prop./Power	11: Common Prop./Power/ECLSS	4: No Hypergols
9	2: Reduce Engines	6: Uniform TPS	7: Robust TPS	3: All Electric
10	8: P-IVHM	4: No Hypergols	3: All Electric	7: Robust TPS
11	11: Common Prop./Power/ECLSS	11: Common Prop./Power/ECLSS	1: Reduce Parts	1: Reduce Parts
12	4: No Hypergols	12: Roll-Up	2: Reduce Engines	2: Reduce Engines

## Appendix E – Context 2 Supporting Material

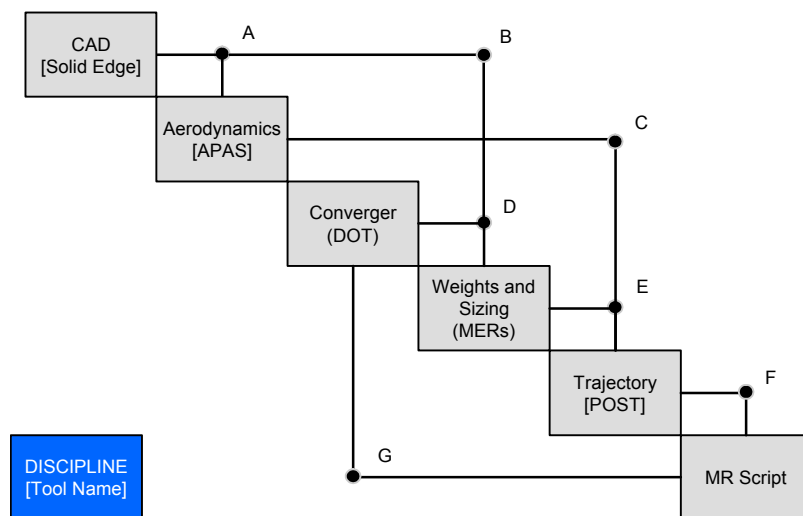


Figure E.1. Design Structure Matrix (DSM) of Performance Assessment Process

### Feed Forward Links

- A: External Geometry of “as-drawn” vehicle elements
- B: External Geometry of “as-drawn” vehicle elements
- C: Tables of longitudinal aerodynamic coefficients
- D: Booster Mass Ratio (guess)  
Orbiter Mass Ratio (guess)
- E: Booster Gross Weight [lbs]  
Orbiter Gross Weight [lbs]  
Booster Total Vacuum Thrust [lbs]  
Orbiter Total Vacuum Thrust [lbs]  
Booster Total Engine Exit Area [ft<sup>2</sup>]  
Orbiter Total Engine Exit Area [ft<sup>2</sup>]  
Booster Sref [ft<sup>2</sup>]  
Orbiter Sref [ft<sup>2</sup>]
- F: Booster Gross Weight [lbs]  
Orbiter Gross Weight [lbs]  
Booster Total Propellant Consumed [lbs]  
Orbiter Total Propellant Consumed [lbs]

### Feedback Links

- G: Calculated Booster Mass Ratio  
Calculated Orbiter Mass Ratio

Figure E.2. List Design Structure Matrix (DSM) Links of Assessment Process

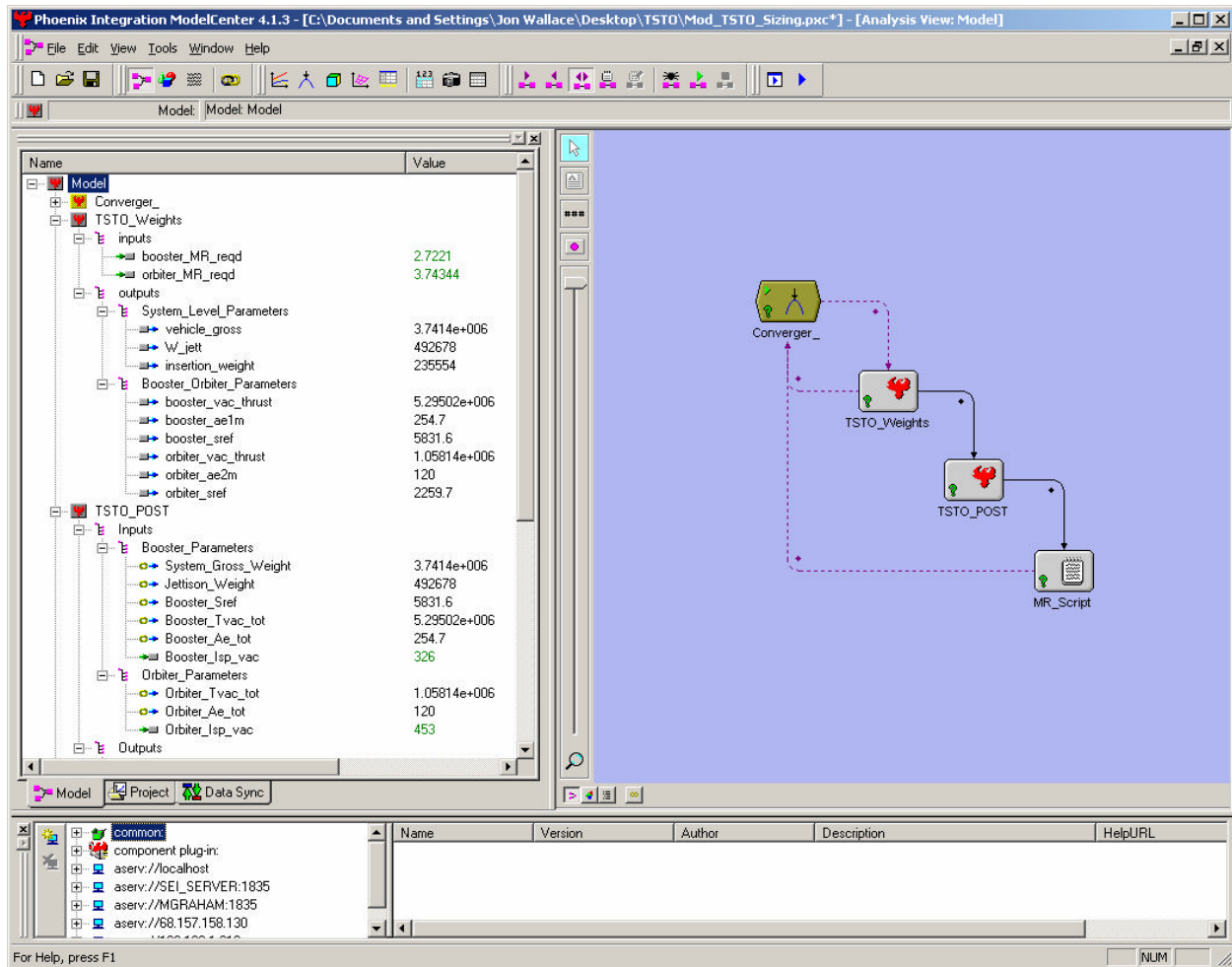


Figure E.3. Vehicle Closure Process in ModelCenter ©  
Collaborative Design Environment

**Table E.1. D4Ops Context 2: Design Assumptions**

Design Category	Context Assumptions
Mission	<ul style="list-style-type: none"> <li>- Fully reusable, TSTO launch vehicle with flyback Booster and glideback Orbiter</li> <li>- Initial Operating Capability (IOC) of 2015</li> <li>- 50,000 payload capability to 120 nmi. circular orbit</li> </ul>
Source / Heritage	<ul style="list-style-type: none"> <li>- Reference TSTO mission taken from NASA NGLT Common Booster TSTO study</li> <li>- Technology assumptions for Context 2 Baseline vehicle from NGLT Ground Rules and Assumptions (GRA) document</li> </ul>
Configuration	<p>Booster:</p> <ul style="list-style-type: none"> <li>- Rocket powered ascent using RS-84 engines (LOX / RP-1)</li> <li>- Wing-body configuration</li> <li>- Airbreathing flyback using F118-GE-100 turbofans</li> </ul> <p>Orbiter:</p> <ul style="list-style-type: none"> <li>- Lifting Body with Wing</li> <li>- Rocket powered using RLX engines (LOX / LH2)</li> <li>- Payload (OSP) carried externally</li> </ul>
Propulsion	<ul style="list-style-type: none"> <li>- 'Rubberized' RS-84 main engines used for Booster stage propulsion (assumed T/W = 73.73)</li> <li>- 'Rubberized' RLX engines used for Orbiter stage main propulsion (assumed T/W = 45.7)</li> <li>- 26 RCS thrusters on both Booster and Orbiter (LOX / Ethanol)</li> <li>- 2 OMS engines on Orbiter stage (LOX / Ethanol)</li> </ul>
Structures	<ul style="list-style-type: none"> <li>- Airframe construction incorporates both Gr-Ep composites and Aluminum 2219 and 2024</li> <li>- Propellant tank materials are Gr-Ep (Booster fuel), Al 2219 (Booster oxidizer), and Al-Li 2195 (Orbiter fuel and oxidizer)</li> </ul>
Thermal Protection System	<ul style="list-style-type: none"> <li>- Little tile shape commonality</li> <li>- Waterproofing required on all</li> <li>- AETB-8/TUFI tiles (leading edges and windward surfaces)</li> <li>- FRSI/AFSI blankets (leeward surfaces)</li> </ul>
Power Generation	<p>Booster Stage</p> <ul style="list-style-type: none"> <li>- 28VDC Li-Ion batteries, 270VDC Batteries (High Voltage Auxiliary Power)</li> <li>- Sized based on 1 day mission</li> </ul> <p>Orbiter Stage</p> <ul style="list-style-type: none"> <li>- 28VDC PEM Fuel Cells (3.5KW average capability each, 7kW assumed total vehicle average power, Qty 4), 270VDC Batteries (High Voltage Auxiliary Power)</li> <li>- Turboalternator device using non-toxic reactants</li> <li>- Sized based on 2 day mission</li> </ul>

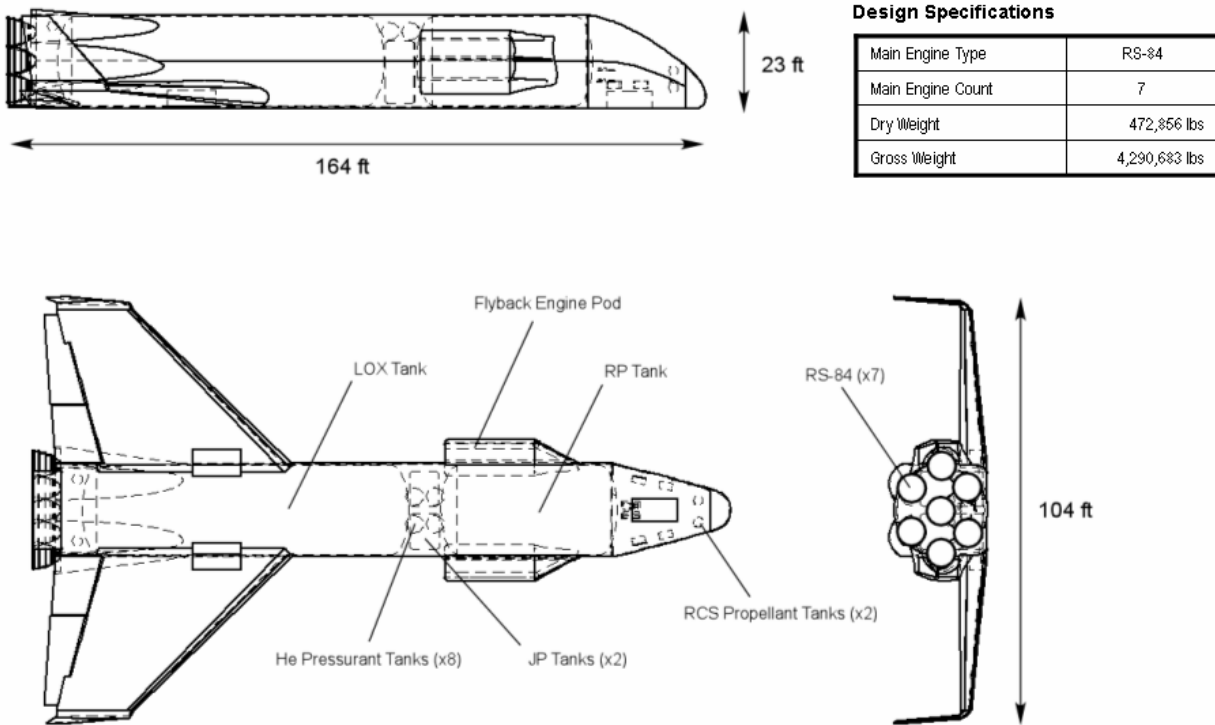


Figure E.4. Context 2 Booster Three-View: Design Approach 0 (SOP)

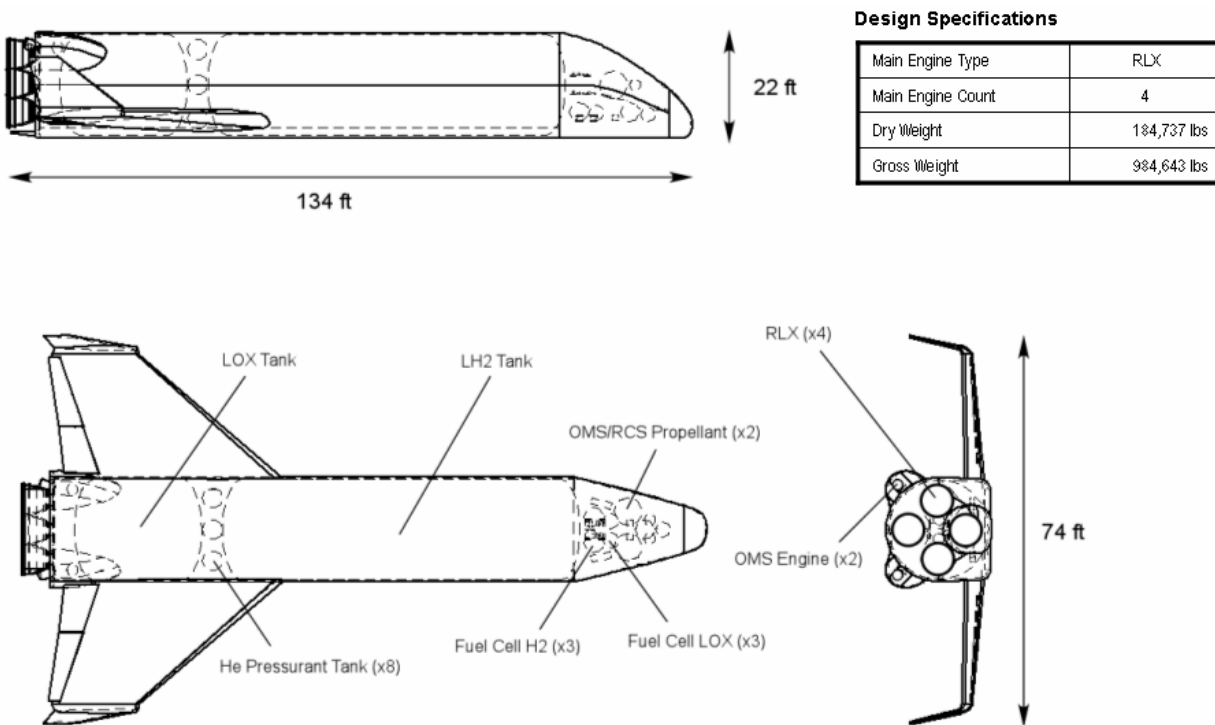


Figure E.5. Context 2 Orbiter Three-View: Design Approach 0 (SOP)

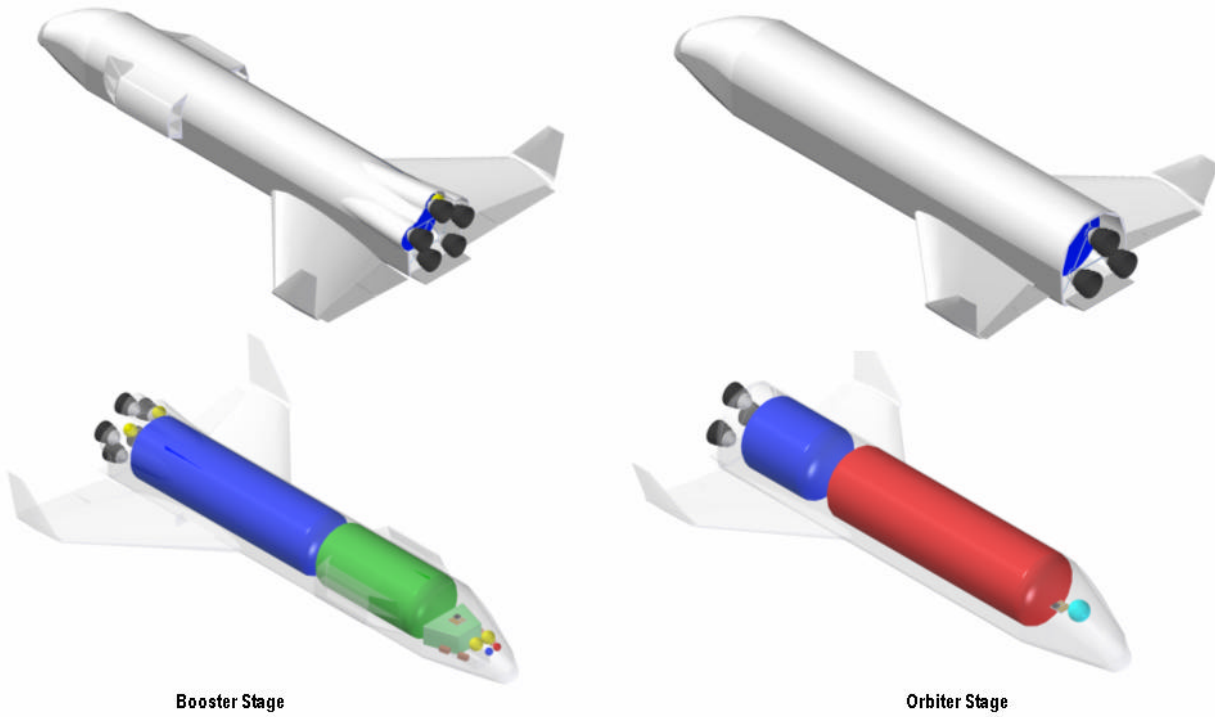
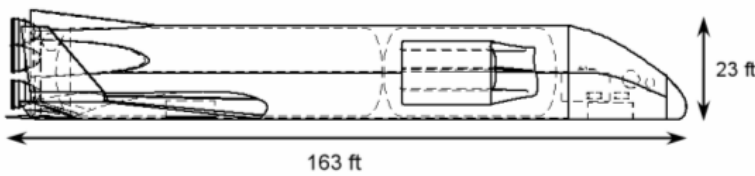


Figure E.6. Context 2 Geometry and Packaging: Design Approach 12 (Roll-up)

**Design Specifications**

Main Engine Type	RS-84
Main Engine Count	5
Dry Weight	466,199 lbs
Gross Weight	4,226,200 lbs

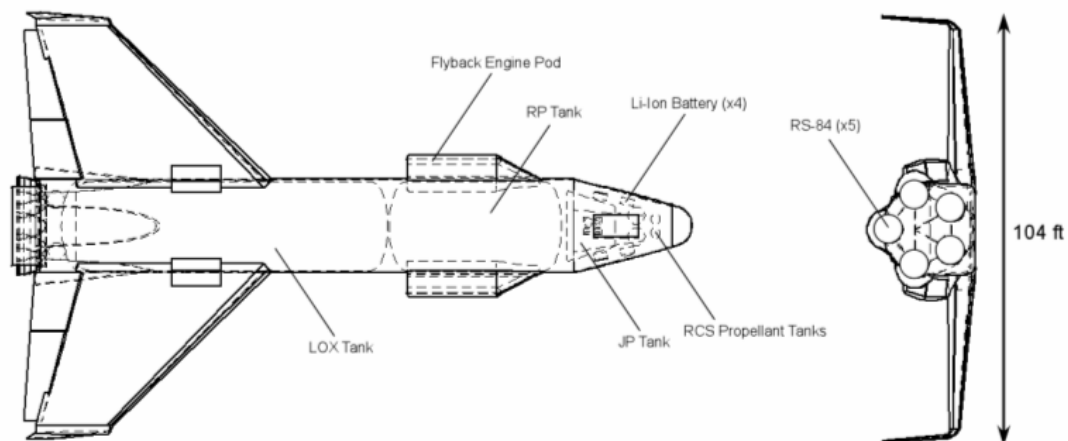


Figure E.7. Context 2 Booster Three-View: Design Approach 12 (Roll-up)

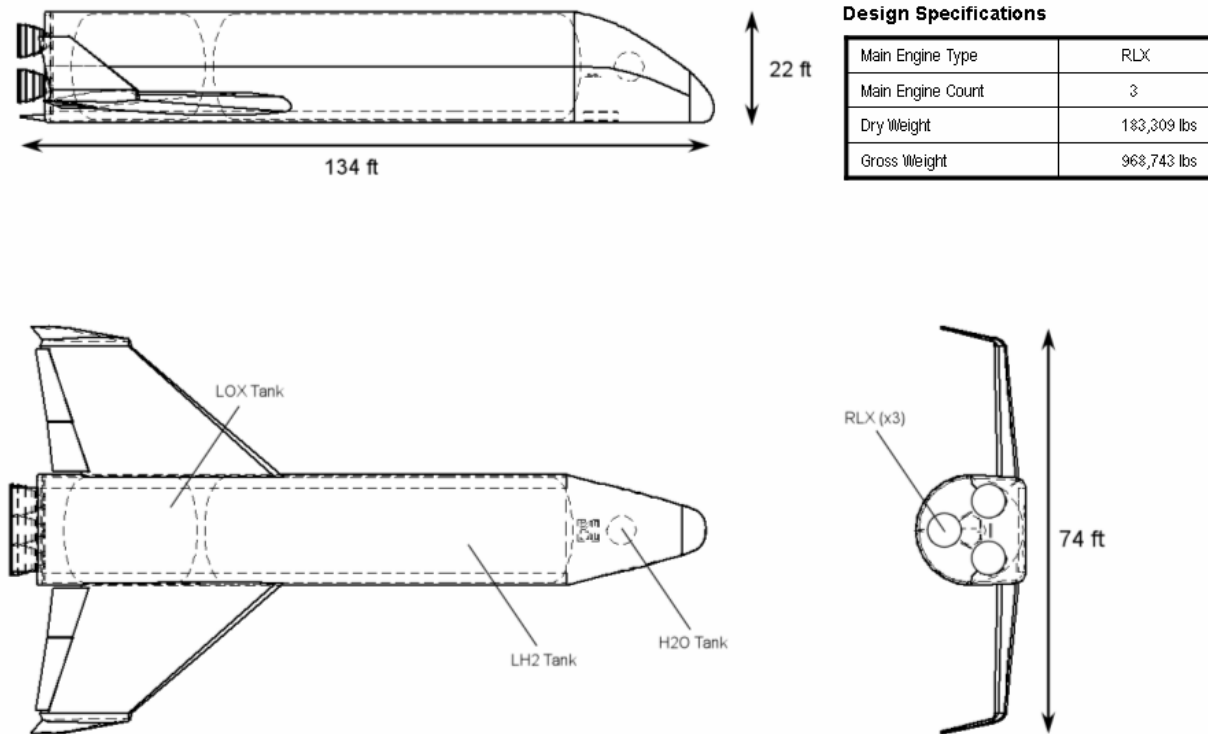


Figure E.8. Context 2 Orbiter Three-View: Design Approach 12 (Roll-up)

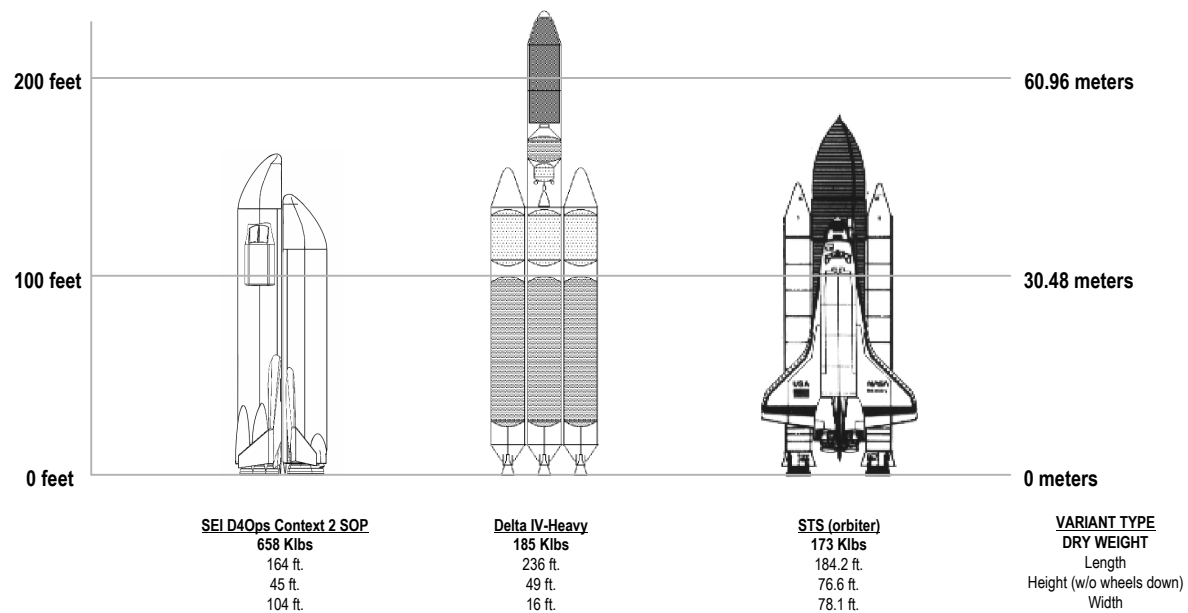
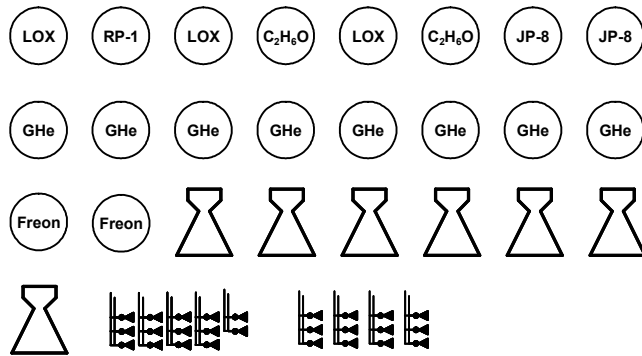
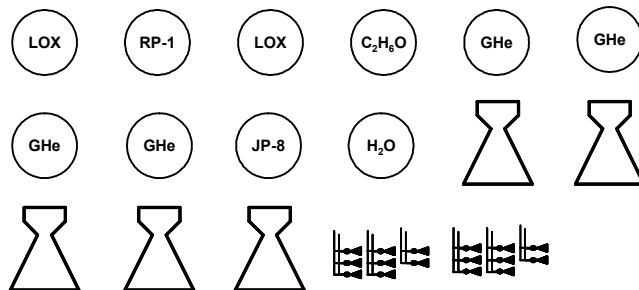


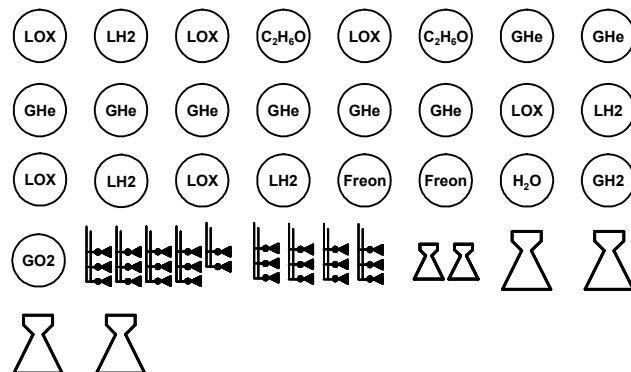
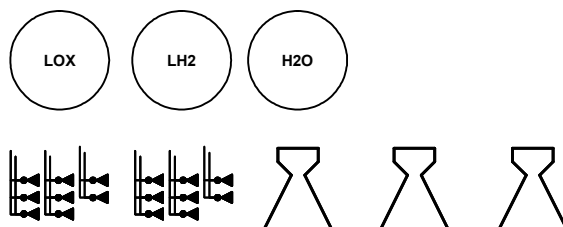
Figure E.9. Context 2 SOP Scale Comparison

**Design Approach 12: Roll-up****Figure E.10. Context 2 Booster Tank/Propulsion Comparison: Approach 0 (SOP) vs. Approach 12 (Roll-up)****SCORECARD**

Number of Main Oxidizer Tanks	1
Number of Main Fuel Tanks	1
Number of Pressurant Tanks (GHe)	8
Number of JP-8 Tanks: Flyback	2
Number of Coolant Tanks (Freon)	2
Number of RCS Oxidizer Tanks	2
Number of RCS Fuel Tanks	2
<b>TOTAL NUMBER OF TANKS</b>	<b>18</b>
Number of Main Engines (RS-84)	7
Number of Nose RCS Thrusters	14
Number of Aft RCS Thrusters	12
Number of OMS Engines	0

**SCORECARD**

Number of Oxidizer Tanks	1
Number of Fuel Tanks	1
Number of Pressurant Tanks (GN2)	4
Number of JP-8 Tanks: Flyback	1
Number of Coolant Tanks (H2O)	1
Number of RCS Oxidizer Tanks	1
Number of RCS Fuel Tanks	1
<b>TOTAL NUMBER OF TANKS</b>	<b>10</b>
Main Engines (RS-84)	5
Number of Nose RCS Thrusters	8
Number of Aft RCS Thrusters	8
Number of OMS Engines	0

**Design Approach 12: Roll-up**

Number of Main Oxidizer Tanks	1
Number of Main Fuel Tanks	1
Number of Pressurant Tanks (GHe)	8
Number of Freon Tanks: Equipment Cooling	2
Number of RCS Oxidizer Tanks	2
Number of RCS Fuel Tanks	2
Number of Fuel Cell LOX Tanks	3
Number of Fuel Cell LH2 Tanks	3
Number of Turboalternator Reactant Tanks	2
Number of Water Tanks	1
<b>TOTAL NUMBER OF TANKS</b>	<b>25</b>
Number of Nose RCS Thrusters	14
Number of Aft RCS Thrusters	12
Number of OMS Engines	2
Number of Main Engines	4

**SCORECARD**

Number of Main Oxidizer Tanks	1
Number of Main Fuel Tanks	1
Number of Pressurant Tanks (GHe)	0
Number of Freon Tanks: Equipment Cooling	0
Number of RCS Oxidizer Tanks	0
Number of RCS Fuel Tanks	0
Number of Fuel Cell LOX Tanks	0
Number of Fuel Cell LH2 Tanks	0
Number of Turboalternator Reactant Tanks	0
Number of Water Tanks	1
<b>TOTAL NUMBER OF TANKS</b>	<b>3</b>
Number of Nose RCS Thrusters	8
Number of Aft RCS Thrusters	8
Number of OMS Engines	0
Number of Main Engines	3

**Figure E.11. Context 2 Orbiter Tank/Propulsion Comparison: Approach 0 (SOP) vs. Approach 12 (Roll-up)**

Table E.2. D4Ops Context 2: Weight Modeling Impacts

Approach	Weight Impact
1: Reduce Parts	<b>Booster:</b> Minimize tank counts (1 LOX tank, 1 RP-1 tank, 4 GHe tanks, 1 RCS LOX tank, 1 RCS Ethanol tank, 1 Freon tank, 1 JP-8 tank); reduce engine counts (5 main engines, 8 aft thrusters, 8 forward thrusters). Resize avionics to reflect zero redundancy (SOP avionics sized for 4x redundancy). <b>Orbiter:</b> Minimize tank counts (1 LOX tank, 1 LH2 tank, 4 GHe tanks, 1 OMS/RCS LOX tank, 1 OMS/RCS Ethanol tank, 2 Fuel Cell reactant tanks, 2 turboalternator reactant tanks, 1 Freon tank, 1 water tank); eliminate redundant fuel cells (1 fuel cell stack with 1 set of reactant tanks); reduce engine counts (3 main engines, 8 aft thrusters, 8 forward thrusters). Resize avionics to reflect zero redundancy (SOP avionics sized for 4x redundancy).
2: Reduce Engines	<b>Booster:</b> Reduce to 5 main engines, 8 aft thrusters, 8 forward thrusters. Reduce RCS system weight by 10%. <b>Orbiter:</b> Reduce to 3 main engines (also used as OMS), 8 aft thrusters, 8 forward thrusters. Reduce RCS system weight by 10%.
3: All Electric	<b>Booster:</b> Not applicable (batteries and EHAs baselined on SOP). <b>Orbiter:</b> Eliminate fuel cell stacks, reactant tankage, and reactants. Size new extended 24 VDC and 270 VDC Li-Ion batteries for entire 2-day mission (high tech @400 W-hr/kg).
4: No Hypergols	<b>Booster:</b> Not applicable. No hypergols present on SOP vehicle. <b>Orbiter:</b> Not applicable. No hypergols present on SOP vehicle.
5: No Hypergols/Cryogens	<b>Booster:</b> Change RCS lsp to 273 sec (H2O2/Ethanol). <b>Orbiter:</b> Change OMS/RCS lsp to 273 sec (H2O2/Ethanol).
6: Uniform TPS	<b>Booster:</b> Add 40% to unit weights for 10% of AETB-8 tile acreage. Add 100% to unit weights for 10% of blanket acreage to account for overall thickness increases. <b>Orbiter:</b> Add 40% to unit weights for 10% of AETB-8 tile acreage. Add 100% to unit weights for 10% of blanket acreage to account for overall thickness increases.
7: Robust TPS	<b>Booster:</b> Reduce overall TPS weight by 100 lb for fewer access panels. Add 0.15 lb/ft <sup>2</sup> for sealing and surface treatment on all acreage weights. <b>Orbiter:</b> Reduce overall TPS weight by 100 lb for fewer access panels. Add 0.15 lb/ft <sup>2</sup> for sealing and surface treatment on all acreage weights.
8: P-IVHM	<b>Booster:</b> Add 500 lb to avionics weight to account for sensors and processors. <b>Orbiter:</b> Add 500 lb to avionics weight to account for sensors and processors.
9: Less Aeroshell	<b>Booster:</b> Repackage propellant tanks to shorten interstage aeroshell. Eliminate base area structure completely. Reduce TPS acreage accordingly. Add 15% weight to each of the following: RCS propulsion, OMS propulsion, ECLSS, and Power for added insulation. <b>Orbiter:</b> Repackage propellant tanks to shorten interstage aeroshell. Eliminate base area structure completely. Reduce TPS acreage accordingly. Add 15% weight to each of the following: RCS propulsion, OMS propulsion, ECLSS, and Power for added insulation.
10: Common Prop/Power	<b>Booster:</b> Not applicable (required fluids for booster power systems not compatible with propulsion system). <b>Orbiter:</b> Increase RCS and OMS system weights by 20%. Increase lsp to 420 sec (LOX/LH2). Eliminate Fuel Cell tanks and tankage weights (leaving 1 unified LOX, 1 unified LH2, 1 water, and 1 Freon tank). Add volume of OMS/RCS propellants and fuel cell reactants to propellant tanks. Add pump machinery to move propellant from main tanks to OMS/RCS.
11: Common Prop/Power/ECLSS	<b>Booster:</b> Not applicable (booster power systems do not require fluids compatible with propulsion system). <b>Orbiter:</b> Increase RCS and OMS system weights by 20%. Increase lsp to 420 sec (LOX/LH2). Eliminate Fuel Cell tanks and tankage weights (leaving 1 unified LOX, 1 unified LH2, 1 water). Add volume of OMS/RCS propellants and fuel cell reactants to propellant tanks. Add pump machinery to move propellant from main tanks to OMS/RCS.
12: Roll-Up	<b>Booster:</b> Reduce to 5 main engines, 8 aft thrusters, 8 forward thrusters. Reduce RCS weight by 10%. Add 40% to acreage unit weights for AETB-8 tiles. Add 100% to acreage unit weights for blankets to account for overall thickness increases. Reduce overall TPS weight by 100 lb for fewer access panels. Add 0.15 lb/ft <sup>2</sup> for sealing and surface treatment on all acreage weights. Add 500 lb to avionics weight to account for sensors and processors (IVHM). Repackage propellant tanks to shorten intertank aeroshell. Eliminate base area structure completely. Reduce TPS acreage accordingly. Add 15% weight to each of the following: RCS propulsion, OMS propulsion, ECLSS, and Power for added insulation. <b>Orbiter:</b> Reduce to 3 main engines (also used as OMS), 8 aft thrusters, 8 forward thrusters. Reduce RCS weight by 10%. Eliminate fuel cell stacks, reactant tankage, and reactants. Size new extended 24 VDC and 270 VDC Li-Ion batteries for entire 2-day mission (high tech @400 W-hr/kg). Add 40% to acreage unit weights for AETB-8 tiles. Add 100% to acreage unit weights for blankets to account for overall thickness increases. Reduce overall TPS weight by 100 lb for fewer access panels. Add 0.15 lb/ft <sup>2</sup> for sealing and surface treatment on all acreage weights. Add 500 lb to avionics weight to account for sensors and processors (IVHM). Repackage propellant tanks to shorten intertank aeroshell. Eliminate base area structure completely. Reduce TPS acreage accordingly. Add 15% weight to each of the following: RCS tankage, ECLSS, and Power for added insulation. Increase RCS and OMS system weights by 20%. Increase lsp to 420 sec (LOX/LH2). Eliminate Fuel Cell tanks and tankage weights (leaving 1 unified LOX, 1 unified LH2, 1 water). Add volume of OMS/RCS propellants and fuel cell reactants to propellant tanks.

Table E.3. D4Ops Context 2: Cost Modeling Impacts

Approach	NAFCOM Non-Recurring Cost Impact
1: Reduce Parts	<b>Booster:</b> Reduce booster main engines to 5. The following applies equally to DDT&E and TFCU complexity factors: Increase avionics complexity by 15% to account for increased monitoring of systems, increase system test hardware by 10%, in order to account for the cost of building more reliable components. <b>Orbiter:</b> Reduce orbiter main engines to 3. The following applies equally to DDT&E and TFCU complexity factors: Increase avionics complexity by 15% to account for increased monitoring of systems, increase system test hardware by 10%, in order to account for the cost of building more reliable components.
2: Reduce Engines	<b>Booster:</b> Reduce booster main engines to 5. The following applies equally to DDT&E and TFCU complexity factors: Increase system test hardware by 5%. In order to account for the cost of building more reliable components increase the complexity on the following CER categories by 5%: OMS, RCS; <b>Orbiter:</b> Reduce orbiter main engines to 3. The following applies equally to DDT&E and TFCU complexity factors: Increase system test hardware by 5%. In order to account for the cost of building more reliable components increase the complexity on the following CER categories by 5%: OMS, RCS;
3: All Electric	<b>Booster:</b> None; <b>Orbiter:</b> The following applies to TFCU complexity factors: decrease power complexity by 20%
4: No Hypergols	<b>Booster:</b> None; <b>Orbiter:</b> None
5: No Hypergols/Cryogens	<b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: Increase OMS/RCS complexity by 15%; <b>Orbiter:</b> <b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: Increase OMS/RCS complexity by 15%
6: Uniform TPS	<b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: reduce TPS complexity by 20%; <b>Orbiter:</b> <b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: reduce TPS complexity by 20%
7: Robust TPS	<b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: Increase TPS complexity by 25%, Increase system test hardware by 5%; <b>Orbiter:</b> The following applies equally to DDT&E and TFCU complexity factors: Increase TPS complexity by 25%, Increase system test hardware by 5%
8: P-IVHM	<b>Booster:</b> Increase avionics complexity by 25%, increase OMS/RCS complexity by 5%, increase system test hardware by 5%; <b>Orbiter:</b> <b>Booster:</b> Increase avionics complexity by 25%, increase OMS/RCS complexity by 5%, increase system test hardware by 5%
9: Less Aeroshell	<b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: Add 20% to System Test Hardware, reduce by 10% Integration, Assembly, & Checkout (IACO). Add 2% to Body complexity, Add 4% to the following: OMS, RCS, Electrical Conversion, Power, and Env; <b>Orbiter:</b> <b>Booster:</b> The following applies equally to DDT&E and TFCU complexity factors: Add 20% to System Test Hardware, reduce by 10% Integration, Assembly, & Checkout (IACO). Add 2% to Body complexity, Add 4% to the following: OMS, RCS, Electrical Conversion, Power, and Env.
10: Common Prop/Power	<b>Booster:</b> None; <b>Orbiter:</b> The following applies equally to DDT&E and TFCU complexity factors: Add 7% to System Test Hardware; Increase the complexity on the following CER categories by 5%: power
11: Common Prop/Power/ECLSS	<b>Booster:</b> none; <b>Orbiter:</b> The following applies equally to DDT&E and TFCU complexity factors: Add 10% to System Test Hardware; Increase the complexity on the following CER categories by 7%: body, power, OMS, RCS, environmental control
12: Roll-Up	<b>Booster:</b> Change booster engines to 5. The following applies equally to DDT&E and TFCU complexity factors: System Test hardware by 53%, Avionics by 43%, Body by 8%, Power by 15%, OMS by 32%, RCS by 32%, Electrical by 5%, TPS by 10%, Environmental Control by 5%, and IACO by -5%; <b>Orbiter:</b> Change orbiter engines to 3. The following applies equally to DDT&E and TFCU complexity factors: System Test hardware by 70%, Avionics by 43%, Body by 8%, Power by 10%, OMS by 48%, RCS by 48%, Electrical by 5%, TPS by 10%, Environmental Control by 10%, and IACO by -5%;

Table E.4. D4Ops Context 2: Safety Modeling Impacts

Approach	GTSafety-II Safety Impact
1: Reduce Parts	Booster: Ground Handling Complexity feature increases to 3.4, Propellant Loading Process feature increases to 3.3, Avionics failure rate decreases by 20%; Orbiter: Ground Handling Complexity feature increases to 3.3, Propellant Loading Process feature increases to 3.4, Avionics failure rate decreases by 20%
2: Reduce Engines	Booster: Ground Handling Complexity feature increased to 3.2; Orbiter: Ground Handling Complexity feature increased to 3.3
3: All Electric	Booster: None; Orbiter: Ground Handling Complexity feature increased to 3.4, Volatile Fluids feature increased to 3.3, Propellant Loading Process feature to 3.2, Decrease electrical system failure rate by 10%, propellant feed system failures reduced by 10%
4: No Hypergols	Booster: None; Orbiter: None
5: No Hypergols/Cryogens	Booster: Ground Handling Complexity increased to 3.3, Safety Factors feature increased to 3.3, Toxic Fluids feature increased to 3.5, Propellant Loading Process feature increased to 3.3, Volatile Fluids feature increased to 3.3; Orbiter: Booster: Ground Handling Complexity increased to 3.3, Safety Factors feature increased to 3.3, Toxic Fluids feature increased to 3.5, Propellant Loading Process feature increased to 3.3, Volatile Fluids feature increased to 3.3
6: Uniform TPS	Booster: Ground Handling Complexity increased to 3.3, no effect on overall end-to-end TPS system failure, Catastrophic TPS Failure/Total TPS Failures decrease to 0.08; Orbiter: Booster: Ground Handling Complexity increased to 3.3, no effect on overall end-to-end TPS system failure, Catastrophic TPS Failure/Total TPS Failures decrease to 0.08
7: Robust TPS	Booster: Decrease TPS failure rate to 1 in 6000, Catastrophic TPS Failure/Total TPS Failures decrease to 0.07, Ground Handling Complexity feature decreased to 3.3; Orbiter: Decrease TPS failure rate to 1 in 6000, Catastrophic TPS Failure/Total TPS Failures decrease to 0.07, Ground Handling Complexity feature decreased to 3.3
8: P-IVHM	Booster: Increase IVHM feature to 3.3, decrease Single Engine Shutdown Rate for Rocket (flights) to 1 in 10000; Orbiter: Increase IVHM feature to 3.3, decrease Single Engine Shutdown Rate for Rocket (flights) to 1 in 10000
9: Less Aeroshell	Booster: Ground Handling Complexity feature increased to 3.3; Orbiter: Ground Handling Complexity feature increased to 3.3
10: Common Prop./Power	Booster: Ground Handling Complexity feature increased to 3.2, Propellant Loading Process feature increased to 3.1, Volatile Fluids feature increased to 3.1; Orbiter: Ground Handling Complexity feature increased to 3.2, Propellant Loading Process feature increased to 3.1, Volatile Fluids feature increased to 3.1
11: Common Prop./Power/ECLSS	Booster: Ground Handling Complexity feature increased to 3.3, Propellant Loading Process feature increased to 3.2, Volatile Fluids feature increased to 3.1; Orbiter: Ground Handling Complexity feature increased to 3.3, Propellant Loading Process feature increased to 3.2, Volatile Fluids feature increased to 3.1
12: Roll-Up	Booster: Ground Handling Complexity feature increased to 3.4, Propellant Loading Process feature increased to 3.4, Volatile Fluids feature increased to 3.2, Toxic Fluids feature increased to 3.5, Safety Factors increased to 3.3, Decrease electrical system failure rate by 20%, propellant feed system failures reduced by 20%, Increase IVHM feature to 3.4, decrease Single Engine Shutdown Rate for Rocket (flights) to 1 in 10000; Orbiter: Ground Handling Complexity feature increased to 3.4, Propellant Loading Process feature increased to 3.4, Volatile Fluids feature increased to 3.2, Toxic Fluids feature increased to 3.5, Safety Factors increased to 3.3, Decrease electrical system failure rate by 20%, propellant feed system failures reduced by 20%, Increase IVHM feature to 3.4, decrease Single Engine Shutdown Rate for Rocket (flights) to 1 in 10000

Table E.5. D4Ops Context 2 Metrics Summary (1 of 3): State of Practice (SOP)

Weight Item	Booster Weight [lbs]	% of Dry Weight	Orbiter Weight [lbs]	% of Dry Weight
Wing Group	38,740	8.2%	12,345	6.7%
Tail Group	4,085	0.9%	2,403	1.3%
Body Group	102,588	21.7%	59,106	32.0%
Thermal Protection	14,250	3.0%	21,050	11.4%
Landing Gear	15,075	3.2%	5,795	3.1%
Main Propulsion	138,004	29.2%	22,703	12.3%
RCS Propulsion	8,399	1.8%	4,873	2.6%
OMS Propulsion	0	0.0%	1,949	1.1%
Flyback Propulsion	39,308	8.3%	0	0.0%
Primary Power	1,675	0.4%	1,655	0.9%
Electrical Conversion and Distribution	3,015	0.6%	3,863	2.1%
EHA Systems	4,500	1.0%	2,954	1.6%
Surface Control Actuation	3,528	0.7%	2,191	1.2%
Avionics	1,850	0.4%	1,647	0.9%
Thermal / Environmental Control	946	0.2%	3,819	2.1%
PVD Systems	1,316	0.3%	1,050	0.6%
Recovery Systems	1,005	0.2%	386	0.2%
Dry Weight Margin	94,571	20.0%	36,947	20.0%
Dry Weight	472,856	100.0%	184,737	100.0%
Cargo (up and down)	0		0	
Residual Propellants	18,211		7,788	
OMS/RCS/Flyback Reserve Propellants	11,422		646	
Landed Weight	502,488		193,171	
Entry/Flyback Propellants	57,416		1,754	
Entry Weight	559,904		194,925	
OMS/RCS Propellants (consumed on-orbit)	0		9,017	
Cargo Discharged	984,643		50,000	
Main Ascent Reserves	27,134		5,799	
Other Inflight Losses and Vents	5,599		0	
Insertion Weight	1,577,280		259,742	
Main Engine Ascent Propellants	2,713,403		724,901	
Gross Liftoff Weight	4,290,683		984,643	

SCORECARD	Booster	Orbiter
Number of Main Oxidizer Tanks	1	1
Number of Main Fuel Tanks	1	1
Number of Pressurant Tanks (GHe)	8	8
Number of JP-8 Tanks: Flyback	2	0
Number of OMS/RCS Oxidizer Tanks	2	2
Number of OMS/RCS Fuel Tanks	2	2
Number of Coolant Tanks	2	2
Number of Fuel Cell Reactant Tanks	0	6
Number of Turboalternator Reactant Tanks	0	2
Number of Water Tanks	0	1
TOTAL NUMBER OF TANKS	18	25
Number of Main Engines (RS-84)	7	4
Number of Nose RCS Thrusters	14	14
Number of Alt RCS Thrusters	12	12
Number of OMS Engines	0	2

DIMENSIONS	
<b>Booster</b>	
Vehicle Length	164 ft
Wingspan	104 ft
Height (w/o gear down)	23 ft
<b>Orbiter</b>	
Vehicle Length	134 ft
Wingspan	74 ft
Height (w/o gear down)	22 ft

<b>System Gross Weight (lbs)</b>	<b>4,290,683</b>
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Table E.6. D4Ops Context 2 Metrics Summary (2 of 3): State of Practice (SOP)

DEVELOPMENT AND ACQUISITION COST METRICS (in FY2003 unless otherwise noted)		SAFETY AND RELIABILITY	
<b>BOOSTER</b>		<b>BOOSTER</b>	
DDT&E: Airframe	\$19,427 M	Loss of Mission (LOM) [Flights]	1 in 287 Flights
DDT&E: Propulsion Set 1 (Liquid Rocket Engine)	\$418 M	Loss of Mission (LOM) Probability	0.99652
DDT&E: Propulsion Set 2 (Fly Back Engine)	\$120 M	Loss of Vehicle (LOV) [Flights]	1 in 533 Flights
Total DDT&E	\$19,965 M	Loss of Vehicle (LOV) Probability	0.99812
<b>BOOSTER</b>		<b>ORBITER</b>	
TFU: Airframe	\$2,635 M	Loss of Mission (LOM) [Flights]	1 in 101 Flights
TFU: Propulsion Set 1 (Liquid Rocket Engine)	\$86 M	Loss of Mission (LOM) Probability	0.99008
TFU: Propulsion Set 2 (Fly Back Engine)	\$9 M	Loss of Vehicle (LOV) [Flights]	1 in 196 Flights
Total Acquisition for 1 Vehicle (with learning effects on engines)	\$627 M	Loss of Vehicle (LOV) Probability	0.99489
<b>ORBITER</b>		<b>ENTIRE VEHICLE</b>	
DDT&E: Airframe	\$18,238 M	Loss of Mission (LOM) [Flights]	1 in 75 Flights
DDT&E: Propulsion Set 1 (Liquid Rocket Engine)	\$293 M	Loss of Mission (LOM) Probability	0.98663
Total DDT&E	\$18,531 M	Loss of Vehicle (LOV) [Flights]	1 in 143 Flights
<b>ORBITER</b>		Loss of Vehicle (LOV) Probability	0.99302
TFU: Airframe	\$2,595 M		
TFU: Propulsion Set 1 (Liquid Rocket Engine)	\$78 M		
Total Acquisition for 1 Vehicle (with learning effects on engines)	\$294 M		
<b>ENTIRE VEHICLE</b>			
DDT&E: Airframe	\$37,664 M		
DDT&E: Propulsion	\$831 M		
Total DDT&E	\$38,496 M		
Acquisition: Airframe-Booster (x1) and Orbiter (x1)	\$5,230 M		
Acquisition: Engines-First Unit (All engines with learning effects)	\$922 M		
<b>COST TO FIRST VEHICLE</b>			
	\$44,648 M		

Table E.7. D4Ops Context 2 Metrics Summary (3 of 3): State of Practice (SOP)

LIFE CYCLE COST METRICS (in FY2003 unless otherwise noted)		OPERATIONS (in FY2003 unless otherwise noted)	
<b>TOTAL FLIGHTS IN PROGRAM</b>		<b>BOOSTER</b>	
FLIGHTS PER YEAR	105 Flights	Fixed Operational: Annual Operations Costs (\$M)	\$775.7 M
	5 Flights Per Year	Total FAC/GSE (nonannualized) (\$M)	\$4,502.8 M
<b>TOTAL PROGRAM COSTS</b>		Variable Costs per Flight (\$M)	\$46.6 M
Life Cycle Costs	\$97,251 M	Max Turn Time (days)	76.1 days
Non-Recurring Costs	\$43,606 M	<b>ORBITER</b>	
Acquisition Costs	\$13,066 M	Fixed Operational: Annual Operations Costs (\$M)	\$903.6 M
Operations Costs	\$40,579 M	Total FAC/GSE (nonannualized) (\$M)	\$344.4 M
<b>ACQUISITION UNITS</b>		Variable Costs per Flight (\$M)	\$54.3 M
Booster Airframes	3	Max Turn Time (days)	79.0 days
Booster Propulsion Set 1 (Liquid Rocket Engines)	21	<b>ENTIRE VEHICLE</b>	
Booster Propulsion Set 2 (Fly back Engines)	24	Fixed Operational: Annual Operations Costs (\$M)	\$1,679.3 M
Boosters Lost Due to Reliability	0	Total FAC/GSE (nonannualized) (\$M)	\$4,847.2 M
Orbiter Airframes	3	Variable Costs per Flight (\$M)	\$100.9 M
Orbiter Propulsion Set 1 (Liquid Rocket Engines)	12	Max Turn Time (days) [Maximum of Booster and 2nd Stage]	79.0 days
Orbiters Lost Due to Reliability	0		
<b>PER FLIGHT COSTS</b>			
Life Cycle Costs	\$926.2 M		
Non-Recurring Costs	\$415.3 M		
Acquisition Costs	\$124.4 M		
Operations Costs	\$386.5 M		

Table E.8. D4Ops Context 2 Metrics Comparison

Item	Dry Weight [lbs]	Gross Liftoff Weight [lbs]	DDT&E Cost [FY2003\$M]	First Unit Acquisition Cost [FY2003\$M]	Loss of Vehicle (LOV) [Reliability]	GSE/Facility Costs (non- annualized) [FY2003\$M]	Ops Costs per Flight (fixed and variable @ 5 flts/yr) [FY2003\$M]	Total Cycle Time [Days]	Total Number of Tanks [Number]
<div></div> Best Answer (Approaches 1-12)									
<div></div> Worst Answer (Approaches 1-12)									
State of Practice (SOP)	657,593	4,290,683	\$38,496	\$6,152	0.99302	\$4,847.2	\$100.9	79.0	25
Approach 1 (Reduce Parts)	628,996	4,112,669	\$38,404	\$5,705	0.99346	\$4,562.5	\$90.0	73.0	14
Approach 2 (Reduce Engines)	640,605	4,188,180	\$38,074	\$5,818	0.99310	\$4,781.2	\$97.5	75.1	25
Approach 3 (All Electric)	646,756	4,220,112	\$37,955	\$6,062	0.99314	\$4,712.2	\$95.0	72.6	15
Approach 4 (No Hypergols)	657,593	4,290,683	\$38,496	\$6,152	0.99302	\$4,847.2	\$100.9	79.0	25
Approach 5 (No Hypergols/Cryogens)	657,735	4,291,546	\$39,282	\$6,286	0.99445	\$4,926.0	\$104.2	82.7	25
Approach 6 (Uniform TPS)	631,623	5,356,128	\$43,555	\$7,100	0.99302	\$5,246.3	\$98.1	75.3	25
Approach 7 (Robust TPS)	690,690	4,493,578	\$42,944	\$6,649	0.99303	\$4,434.8	\$92.8	70.9	25
Approach 8 (P-IVHM)	664,834	4,333,431	\$40,510	\$6,255	0.99461	\$4,024.6	\$84.0	66.2	25
Approach 9 (Less Aeroshell)	627,878	4,113,349	\$40,202	\$6,047	0.99302	\$4,025.5	\$87.5	65.5	25
Approach 10 (Common Prop./Power)	668,482	4,345,337	\$39,873	\$6,274	0.99302	\$4,064.8	\$74.5	62.3	5
Approach 11 (Common Prop./Power/ECLSS)	666,135	4,330,993	\$40,705	\$6,350	0.99302	\$4,746.4	\$75.0	70.9	3
Approach 12 (Roll-up)	797,607	5,119,763	\$63,539	\$7,650	0.99678	\$3,232.6	\$61.6	55.2	3
<b>Difference from State of Practice (SOP)</b>									
State of Practice (SOP)	0.0%	0.0%	0.0%	0.0%	0.000%	0.0%	0.0%	0.0%	0.0%
Approach 1 (Reduce Parts)	-4.3%	-4.1%	-0.2%	-7.3%	0.044%	-5.9%	-10.8%	-7.6%	-44.0%
Approach 2 (Reduce Engines)	-2.6%	-2.4%	-1.1%	-5.4%	0.008%	-1.4%	-3.4%	-4.9%	0.0%
Approach 3 (All Electric)	-1.6%	-1.6%	-1.4%	-1.5%	0.012%	-2.8%	-5.8%	-8.1%	-40.0%
Approach 4 (No Hypergols)	0.0%	0.0%	0.0%	0.0%	0.000%	0.0%	0.0%	0.0%	0.0%
Approach 5 (No Hypergols/Cryogens)	0.0%	0.0%	2.0%	2.2%	0.144%	1.6%	3.3%	4.7%	0.0%
Approach 6 (Uniform TPS)	26.5%	24.8%	13.1%	15.4%	0.000%	8.2%	-2.7%	-4.7%	0.0%
Approach 7 (Robust TPS)	5.0%	4.7%	11.6%	8.1%	0.002%	-8.5%	-8.0%	-10.3%	0.0%
Approach 8 (P-IVHM)	1.1%	1.0%	5.2%	1.7%	0.160%	-17.0%	-16.8%	-16.2%	0.0%
Approach 9 (Less Aeroshell)	-4.5%	-4.1%	4.4%	-1.7%	0.000%	-17.0%	-13.3%	-17.1%	0.0%
Approach 10 (Common Prop./Power)	1.7%	1.3%	3.6%	2.0%	0.000%	-16.1%	-26.2%	-21.1%	-80.0%
Approach 11 (Common Prop./Power/ECLSS)	1.3%	0.9%	5.7%	3.2%	0.000%	-2.1%	-25.6%	-10.3%	-88.0%
Approach 12 (Roll-up)	21.3%	19.3%	65.1%	24.3%	0.378%	-33.3%	-38.9%	-30.1%	-88.0%

Table E.9. D4Ops Context 2: Life Cycle Costs (LCC) Metrics Comparison

Item	Life Cycle Cost at 5 Flights/Year	Life Cycle Cost Per Flight at 5 Flights/Year	Non-Recurring Cost Per Flight at 5 Flights/Year	Acquisition Cost Per Flight at 5 Flights/Year	Operations Cost Per Flight at 5 Flights/Year
Best Answer (Approaches 1-12)	[FY2003\$M]	[FY2003\$/Flight]	[FY2003\$/Flight]	[FY2003\$/Flight]	[FY2003\$/Flight]
Worst Answer (Approaches 1-12)					
State of Practice (SOP)	\$97,251.1	\$926.2	\$415.3	\$124.4	\$386.5
Approach 1 (Reduce Parts)	\$91,187.2	\$868.4	\$413.1	\$116.7	\$338.7
Approach 2 (Reduce Engines)	\$94,760.9	\$902.5	\$411.9	\$118.3	\$372.3
Approach 3 (All Electric)	\$94,043.7	\$895.7	\$408.9	\$123.4	\$363.4
Approach 4 (No Hypergols)	\$97,251.1	\$926.2	\$415.3	\$124.4	\$386.5
Approach 5 (No Hypergols/Cryogenics)	\$99,251.5	\$945.3	\$423.4	\$126.2	\$395.6
Approach 6 (Uniform TPS)	\$103,842.2	\$989.0	\$467.8	\$141.1	\$380.0
Approach 7 (Robust TPS)	\$98,996.4	\$942.8	\$454.4	\$131.3	\$357.1
Approach 8 (P-IVHM)	\$91,638.1	\$872.7	\$427.6	\$126.0	\$319.1
Approach 9 (Less Aeroshell)	\$92,454.1	\$880.5	\$424.5	\$122.5	\$333.6
Approach 10 (Common Prop./Power)	\$86,922.2	\$827.8	\$421.9	\$125.3	\$280.7
Approach 11 (Common Prop./Power/ECLSS)	\$88,203.6	\$840.0	\$435.5	\$125.0	\$279.5
Approach 12 (Roll-up)	\$97,989.4	\$933.2	\$639.3	\$144.4	\$149.5
<b>Difference from State of Practice (SOP)</b>					
State of Practice (SOP)	0.0%	0.0%	0.0%	0.0%	0.0%
Approach 1 (Reduce Parts)	-6.2%	-6.2%	-0.5%	-6.2%	-12.4%
Approach 2 (Reduce Engines)	-2.6%	-2.6%	-0.8%	-4.9%	-3.7%
Approach 3 (All Electric)	-3.3%	-3.3%	-1.5%	-0.9%	-6.0%
Approach 4 (No Hypergols)	0.0%	0.0%	0.0%	0.0%	0.0%
Approach 5 (No Hypergols/Cryogenics)	2.1%	2.1%	2.0%	1.4%	2.4%
Approach 6 (Uniform TPS)	6.8%	6.8%	12.7%	13.4%	-1.7%
Approach 7 (Robust TPS)	1.8%	1.8%	9.4%	5.5%	-7.6%
Approach 8 (P-IVHM)	-5.8%	-5.8%	3.0%	1.2%	-17.4%
Approach 9 (Less Aeroshell)	-4.9%	-4.9%	2.2%	-1.6%	-13.7%
Approach 10 (Common Prop./Power)	-10.6%	-10.6%	1.6%	0.7%	-27.4%
Approach 11 (Common Prop./Power/ECLSS)	-9.3%	-9.3%	4.9%	0.5%	-27.7%
Approach 12 (Roll-up)	0.8%	0.8%	53.9%	16.1%	-61.3%

Table E.10. D4Ops Context 2: Metrics Comparison (Normalized)

Item	Dry Weight [lbs]	Gross Liftoff Weight [lbs]	DDT&E Cost [FY2003\$M]	First Unit Acquisition Cost [FY2003\$M]	Loss of Vehicle (LOV) [Reliability]	GSE/Facility Costs (non-annualized) [FY2003\$M]	Ops Costs per Flight (fixed and variable @ 5 flts/yr) [FY2003\$M]	Total Cycle Time [Days]	Total Number of Tanks [Number]
Best Answer (Approaches 1-12)									
Worst Answer (Approaches 1-12)									
State of Practice (SOP)	100	100	100	100	100	100	100	100	25
Approach 1 (Reduce Parts)	96	96	100	93	100	94	89	92	14
Approach 2 (Reduce Engines)	97	98	99	95	100	99	97	95	25
Approach 3 (All Electric)	98	98	99	99	100	97	94	92	15
Approach 4 (No Hypergols)	100	100	100	100	100	100	100	100	25
Approach 5 (No Hypergols/Cryogenics)	100	100	102	102	100	102	103	105	25
Approach 6 (Uniform TPS)	126	125	113	115	100	108	97	95	25
Approach 7 (Robust TPS)	105	105	112	108	100	91	92	90	25
Approach 8 (P-IVHM)	101	101	105	102	100	83	83	84	25
Approach 9 (Less Aeroshell)	95	96	104	98	100	83	87	83	25
Approach 10 (Common Prop./Power)	102	101	104	102	100	84	74	79	5
Approach 11 (Common Prop./Power/ECLSS)	101	101	106	103	100	98	74	90	3
Approach 12 (Roll-up)	121	119	165	124	100	67	61	70	3

Table E.11. D4Ops Context 2: Life Cycle Cost (LCC) Metrics Comparison (Normalized)

Item	Life Cycle Cost at 5 Flights/Year	Life Cycle Cost Per Flight at 5 Flights/Year	Non-Recurring Cost Per Flight at 5 Flights/Year	Acquisition Cost Per Flight at 5 Flights/Year	Operations Cost Per Flight at 5 Flights/Year
<div></div> Best Answer (Approaches 1-12)	[FY2003\$M]	[FY2003\$/Flight]	[FY2003\$/Flight]	[FY2003\$/Flight]	[FY2003\$/Flight]
<div></div> Worst Answer (Approaches 1-12)					
State of Practice (SOP)	100	100	100	100	100
Approach 1 (Reduce Parts)	94	94	99	94	88
Approach 2 (Reduce Engines)	97	97	99	95	96
Approach 3 (All Electric)	97	97	98	99	94
Approach 4 (No Hypergols)	100	100	100	100	100
Approach 5 (No Hypergols/Cryogens)	102	102	102	101	102
Approach 6 (Uniform TPS)	107	107	113	113	98
Approach 7 (Robust TPS)	102	102	109	106	92
Approach 8 (P-IVHM)	94	94	103	101	83
Approach 9 (Less Aeroshell)	95	95	102	98	86
Approach 10 (Common Prop./Power)	89	89	102	101	73
Approach 11 (Common Prop./Power/ECLSS)	91	91	105	100	72
Approach 12 (Roll-up)	101	101	154	116	39

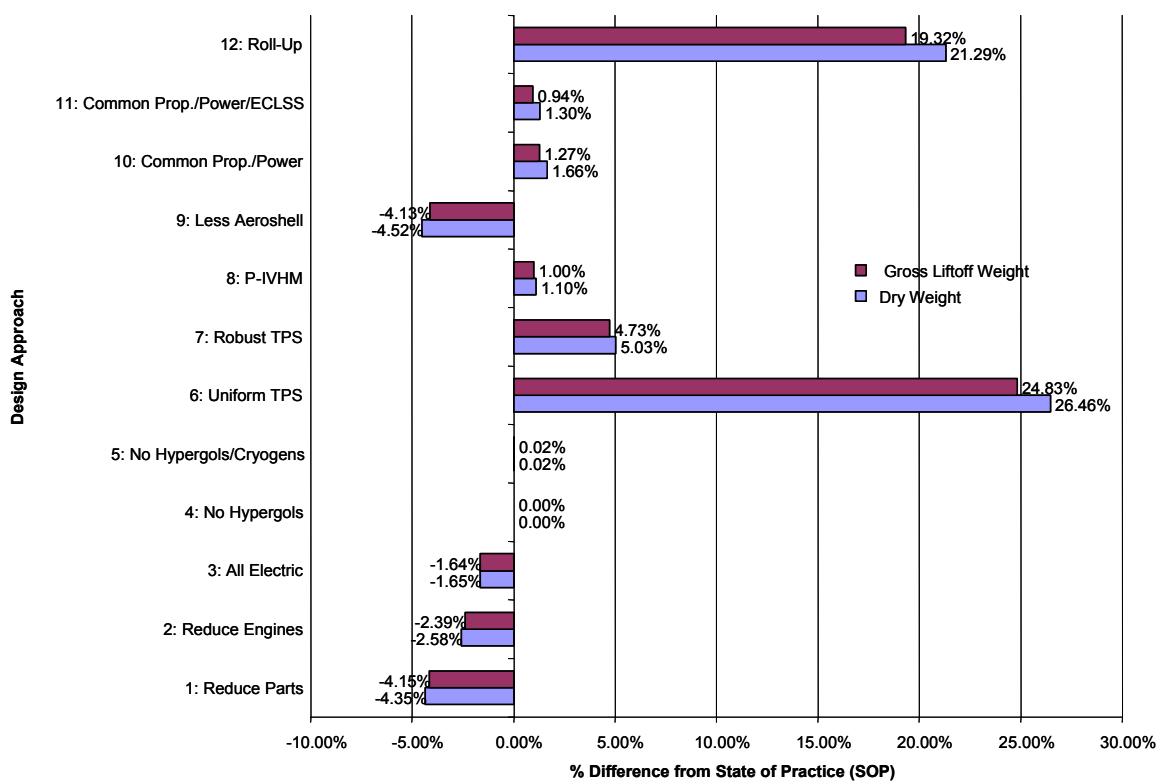


Figure E.12. D4Ops Context 2: Weight Metric Comparison to SOP

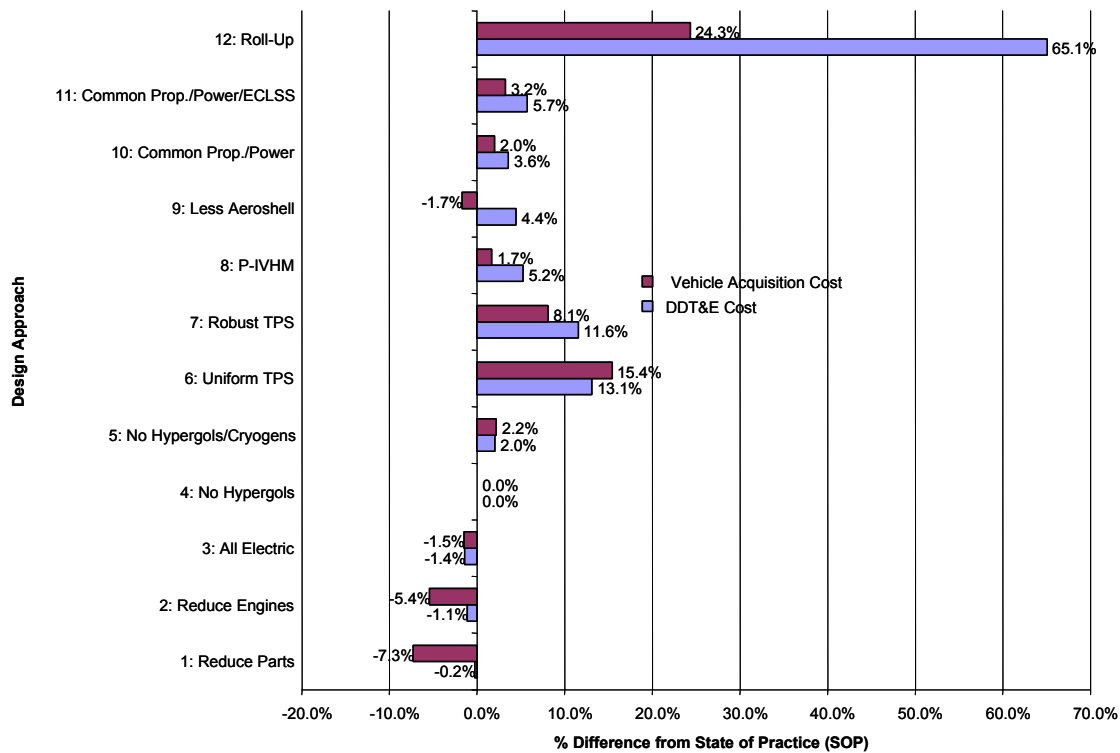


Figure E.13. D4Ops Context 2: Non-recurring Cost Metric Comparison to SOP

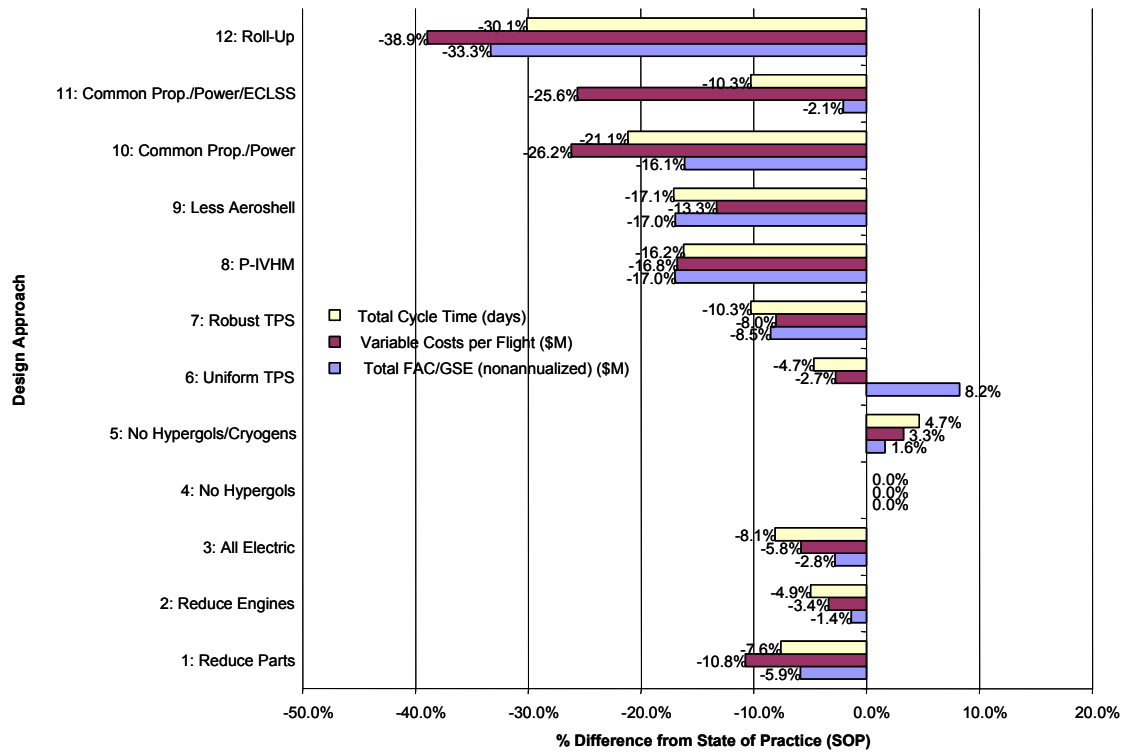


Figure E.14. D4Ops Context 2: Operations Metric Comparison to SOP

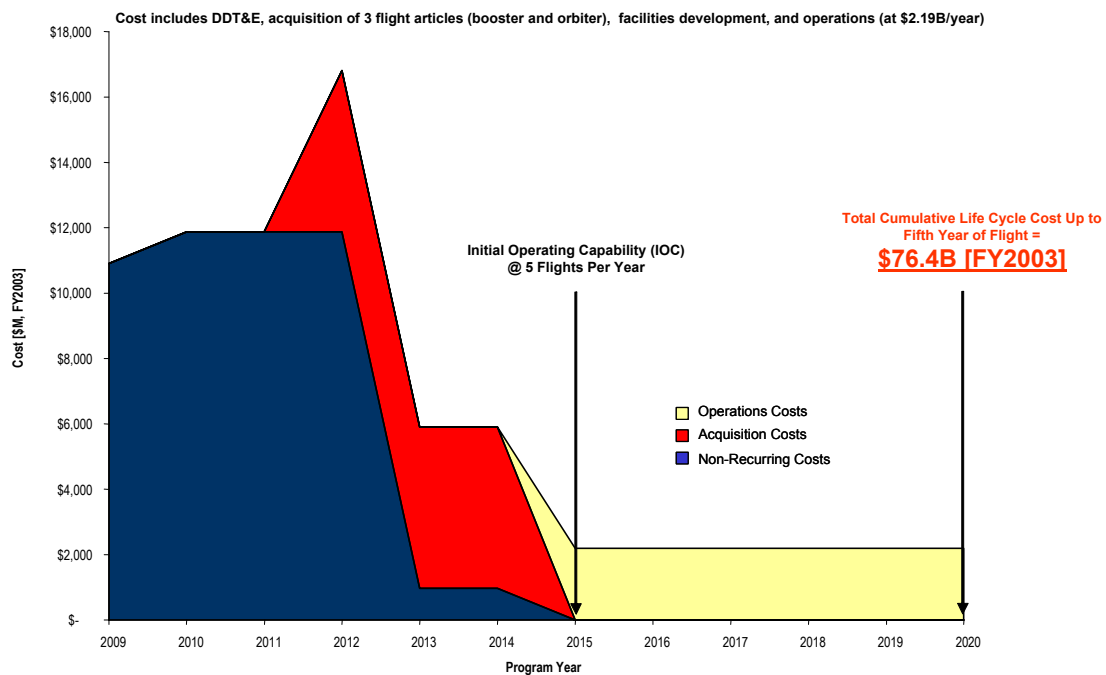


Figure E.15. D4Ops Context 2 State of Practice: Initial Cost

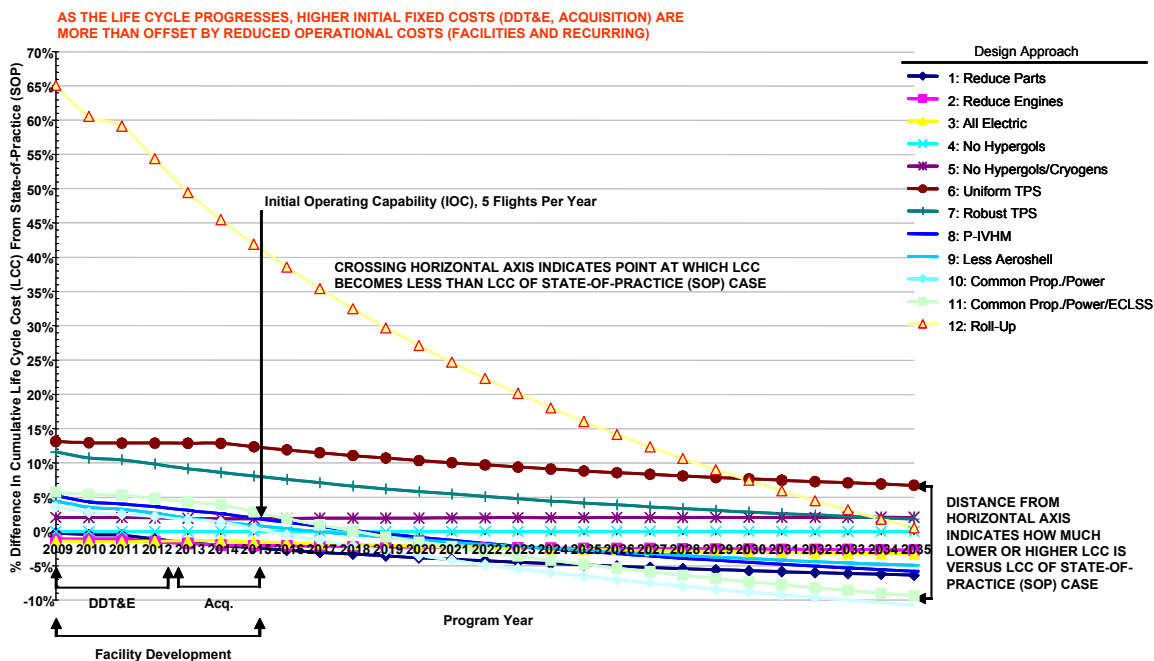


Figure E.16. D4Ops Context 2: Cumulative Life Cycle Cost Comparison to SOP

Table E.12. D4Ops Context 2: OEC Components and Weight Scenarios

Overall Evaluation Criteria (OEC) Components [PREFERENCE]	Weighting Scenarios									
	Even	Weight	Non-Recur. Cost	Cycle Time/Var. Cost	Safety	Ops Cost	Life Cycle Cost	Cycle Time and Safety	DDT&E and GSE	Cycle Time
Dry Weight [MINIMIZE]	11%	43%	2%	2%	2%	2%	2%	2%	2%	2%
Gross Liftoff Weight (with CES) [MINIMIZE]	11%	43%	2%	2%	2%	2%	2%	2%	2%	2%
DDT&E Cost [MINIMIZE]	11%	2%	86%	2%	2%	2%	2%	2%	43%	2%
TFU Cost [MINIMIZE]	11%	2%	2%	2%	2%	2%	2%	2%	2%	2%
LOV Reliability [MAXIMIZE]	11%	2%	2%	2%	84%	2%	2%	43%	2%	2%
GSE/Facility: Non-Annualized (\$M) [MINIMIZE]	11%	2%	2%	2%	2%	43%	2%	2%	43%	2%
Variable Costs per Flight (\$M) [MINIMIZE]	11%	2%	2%	43%	2%	43%	2%	2%	2%	2%
Total Cycle Time (days) [MINIMIZE]	11%	2%	2%	43%	2%	2%	2%	43%	2%	84%
Life Cycle Cost [\$M] at 4 Flights/Year [MINIMIZE]	11%	2%	2%	2%	2%	2%	84%	2%	2%	2%

Table E.13. D4Ops Context 2: Rank Across Weighting Scenarios

Design Approach	Median of Ranks	Standard Deviation of Ranks	Rank Across Weighting Scenarios [1=best]									
			Even	Weight	Non-Recur. Cost	Cycle Time/ Var. Cost	Safety	Ops Cost	Life Cycle Costs	Cycle Time and Safety	DDT&E and GSE	Cycle Time
1: Reduce Parts	5.0	2.1	5	2	3	6	5	6	3	8	4	8
2: Reduce Engines	7.0	2.5	7	3	2	9	7	9	7	9	7	9
3: All Electric	6.0	2.1	6	4	1	8	6	8	6	7	5	7
4: No Hypergols	9.0	2.5	9	5	4	11	9	10	8	11	8	11
5: No Hypergols/Cryogens	11.0	2.5	11	6	5	12	11	11	11	12	10	12
6: Uniform TPS	11.5	0.9	12	12	11	10	12	12	12	10	11	10
7: Robust TPS	7.5	1.7	8	10	10	7	8	7	10	6	6	6
8: P-IVHM	4.0	2.0	3	7	8	4	2	3	4	4	2	4
9: Less Aeroshell	3.0	1.9	2	1	7	5	3	4	5	3	1	3
10: Common Prop./Power	2.0	2.6	1	9	6	2	1	2	1	2	3	2
11: Common Prop./Power/ECLSS	5.0	2.5	4	8	9	3	4	5	2	5	9	5
12: Roll-Up	9.5	5.1	10	11	12	1	10	1	9	1	12	1

Table E.14. D4Ops Context 2: Final Rank Across Several Weighting Scenarios

Rank [1=best]	Even Across 9 FOMs	Weight	Cycle Time	Life Cycle Costs
1	10: Common Prop./Power	9: Less Aeroshell	12: Roll-Up	10: Common Prop./Power
2	9: Less Aeroshell	1: Reduce Parts	10: Common Prop./Power	11: Common Prop./Power/ECLSS
3	8: P-IVHM	2: Reduce Engines	9: Less Aeroshell	1: Reduce Parts
4	11: Common Prop./Power/ECLSS	3: All Electric	8: P-IVHM	8: P-IVHM
5	1: Reduce Parts	4: No Hypergols	11: Common Prop./Power/ECLSS	9: Less Aeroshell
6	3: All Electric	5: No Hypergols/Cryogens	7: Robust TPS	3: All Electric
7	2: Reduce Engines	8: P-IVHM	3: All Electric	2: Reduce Engines
8	7: Robust TPS	11: Common Prop./Power/ECLSS	1: Reduce Parts	4: No Hypergols
9	4: No Hypergols	10: Common Prop./Power	2: Reduce Engines	12: Roll-Up
10	12: Roll-Up	7: Robust TPS	6: Uniform TPS	7: Robust TPS
11	5: No Hypergols/Cryogens	12: Roll-Up	4: No Hypergols	5: No Hypergols/Cryogens
12	6: Uniform TPS	6: Uniform TPS	5: No Hypergols/Cryogens	6: Uniform TPS

## Appendix F – Context 3 Supporting Material

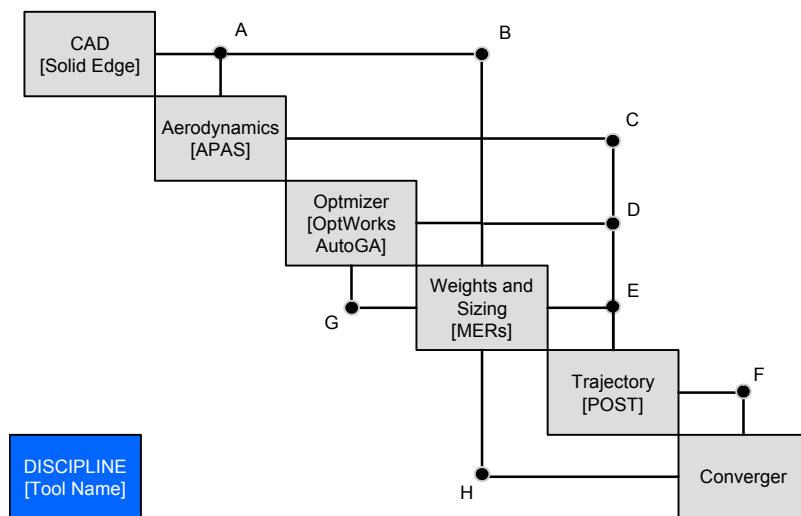


Figure F.1. Design Structure Matrix (DSM) for Context 3a and 3b Performance Closure

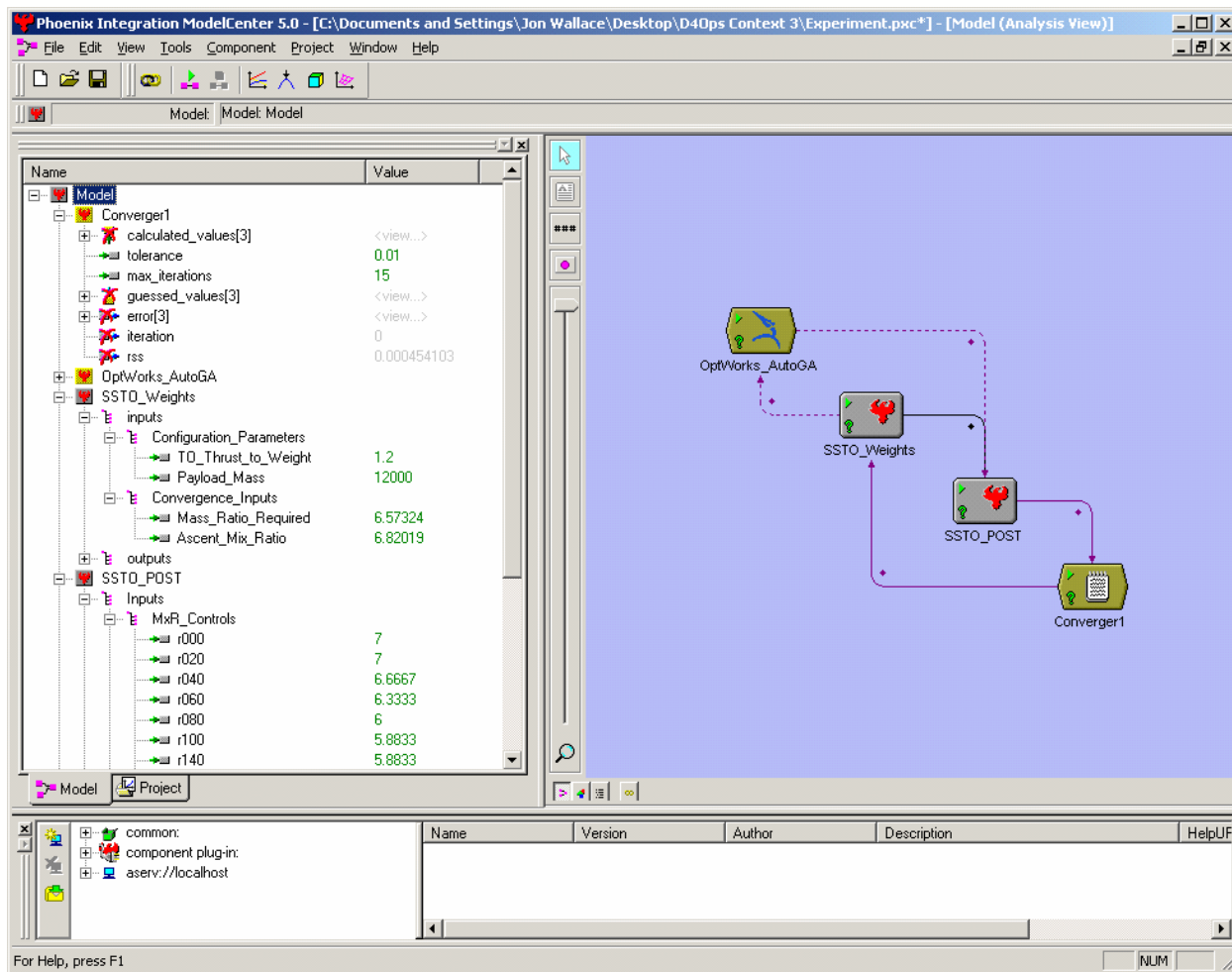
### Feed Forward Links

- A: External Geometry of “as-drawn” vehicle elements
- B: External Geometry of “as-drawn” vehicle elements
- C: Tables of longitudinal aerodynamic coefficients
- D: Mixture Ratio Schedule (function of time)
- E: Gross Weight [lbs]  
Total Vacuum Thrust [lbs]  
Total Engine Exit Area [ft<sup>2</sup>]  
Sref [ft<sup>2</sup>]
- F: Mass Ratio (simulation output)  
Overall Vehicle Mixture Ratio (simulation output)

### Feedback Links

- G: Calculated Vehicle Gross Weight
- H: Mass Ratio (guess)  
Overall Vehicle Mixture Ratio (guess)

Figure F.2. Design Structure Matrix (DSM) Links for Performance Closure



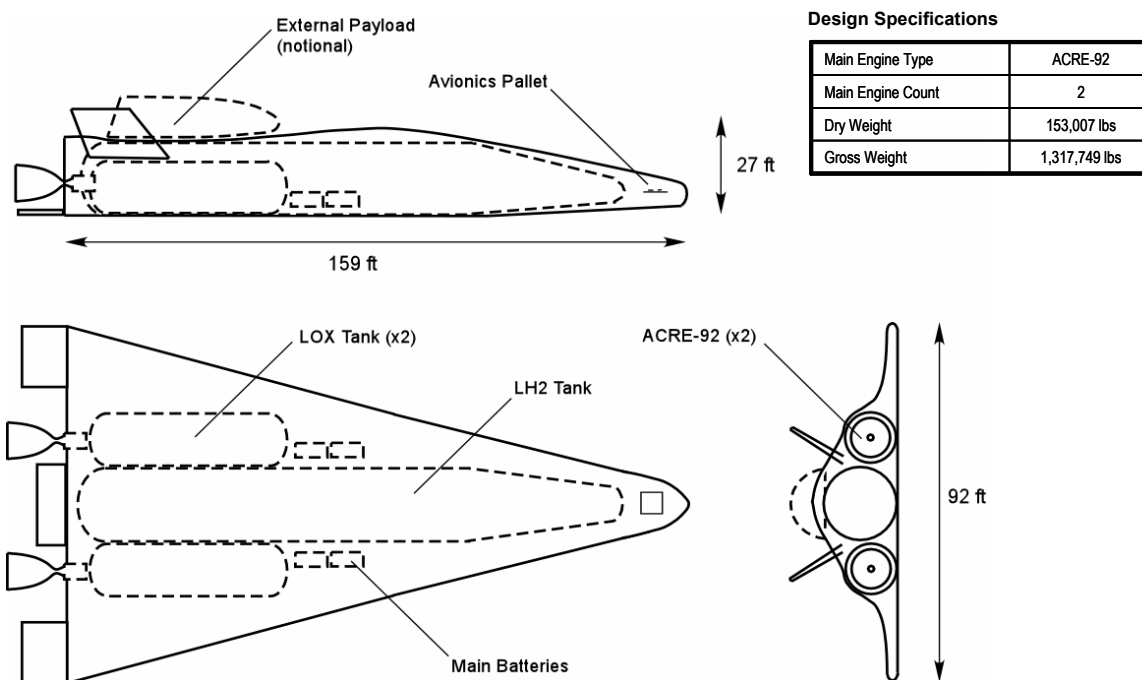
**Figure F.3. Vehicle Closure Process in ModelCenter © Collaborative Design Environment**

**Table F.1. D4Ops Context 3 Design Assumptions (1 of 2)**

Design Category	Context Properties
Mission	<ul style="list-style-type: none"> <li>- Fully reusable, all-rocket, SSTO launch vehicle</li> <li>- Initial Operating Capability (IOC) of 2020</li> <li>- 12,000 payload capability to 100 nmi. circular orbit (DARPA)</li> </ul>
Source / Heritage	<ul style="list-style-type: none"> <li>- Reference SSTO mission (final orbit and payload weight) taken from DARPA Operational Responsive Spacelift (ORS) Force Application and Launch from CONUS (FALCON) program specifications</li> <li>- Technology assumptions for Context 3 vehicles from various historical SSTO studies and past SEI experience</li> </ul>
Configuration	<ul style="list-style-type: none"> <li>- Rocket powered ascent using ACRE-92 engines (LOX / LH2)</li> <li>- Variable Mixture Ratio during ascent</li> <li>- Lifting Body shape with tail fins (based in part on X-24b research vehicle)</li> <li>- Payload pod carried externally</li> <li>- <u>Context 3a</u>: Removable main propellant tanks</li> <li>- <u>Context 3b</u>: Modular, partially integral propellant tanks</li> </ul>

**Table F.2. D4Ops Context 3 Design Assumptions (2 of 2)**

Design Category	Context Properties
Propulsion	<ul style="list-style-type: none"> <li>- 'Rubberized' ACRE-92 main engines used for ascent propulsion (assumed T/W = 92)</li> <li>- RCS thrusters (LOX / LH2)</li> <li>- OMS omitted in favor of orbital maneuvering via throttled MPS</li> </ul>
Structures	<ul style="list-style-type: none"> <li>- Airframe construction incorporates Gr-Ep composites</li> <li>- Propellant tank material is Al-Li for both oxidizer and fuel</li> </ul>
Thermal Protection System	<ul style="list-style-type: none"> <li>- High degree of tile shape commonality</li> <li>- Waterproofing assumed required</li> <li>- Ti-Inconel metallic TPS on windward surfaces</li> <li>- Lightweight TABI blanket TPS on leeward surfaces</li> </ul>
Power Generation	<ul style="list-style-type: none"> <li>- 28VDC Li-Ion batteries, 270VDC Batteries (High Voltage Auxiliary Power)</li> <li>- Sized based on 1 day mission</li> </ul>

**Figure F.4. D4Ops Context 3a Three-view Drawing**

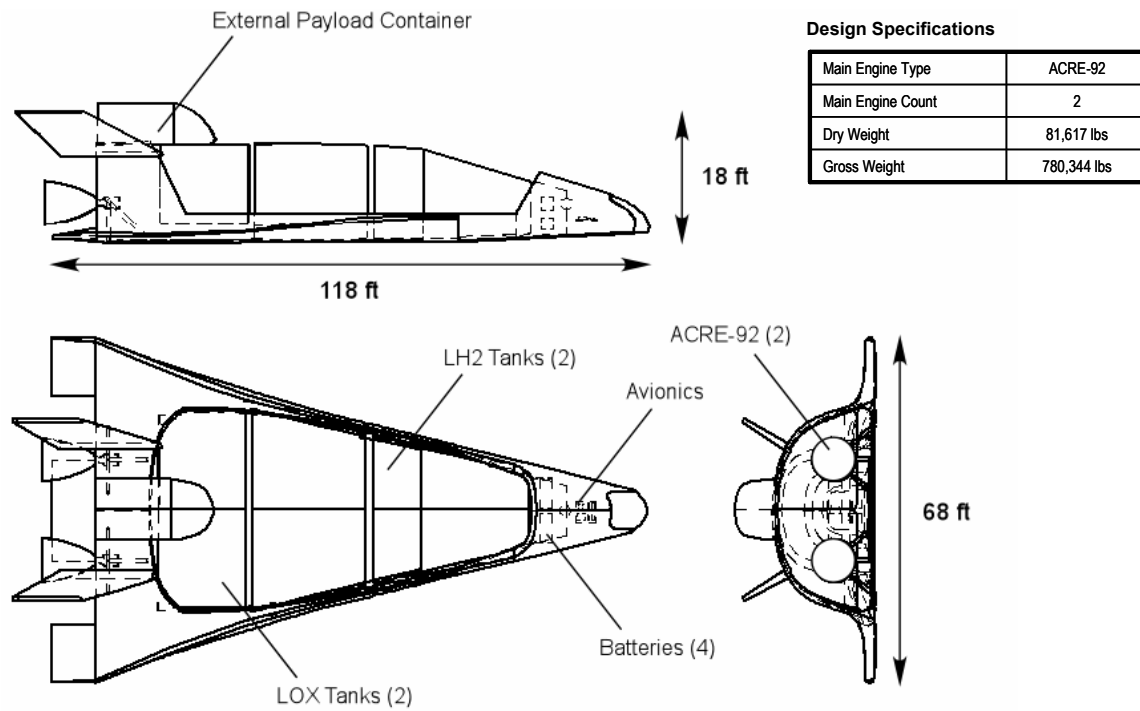


Figure F.5. D4Ops Context 3b Three-view Drawing

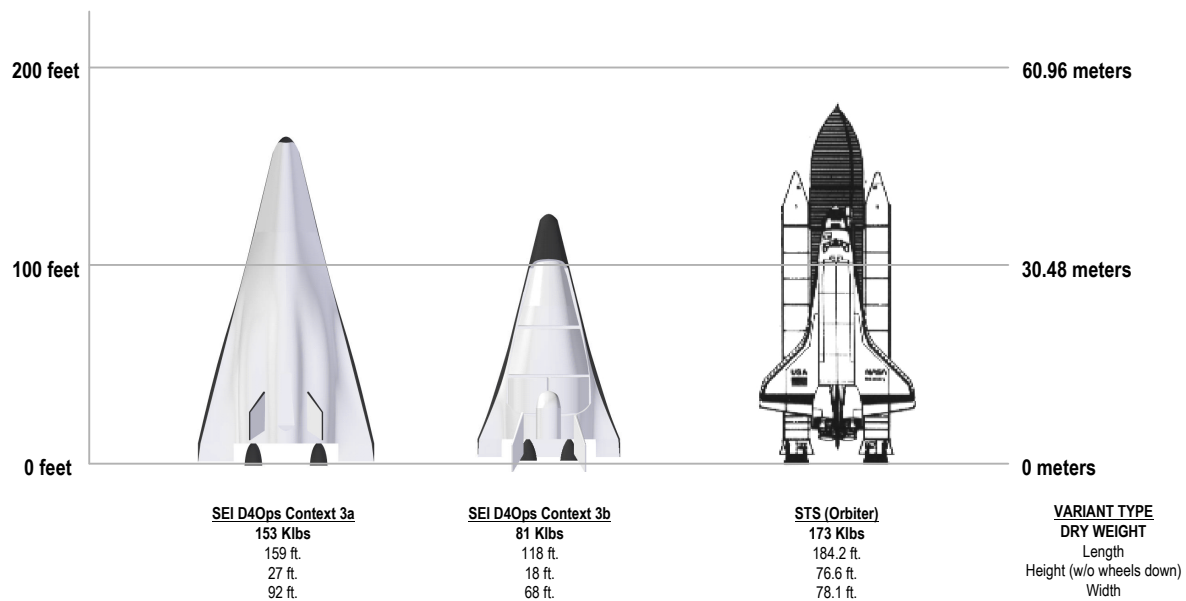


Figure F.6. D4Ops Context 3 Scale Comparison

Table F.3. D4Ops Context 3a Metrics Summary

Weight Item	Weight [lbs]	% of Dry Weight
Tail Group	4,744	3.1%
Body Group	76,609	50.1%
Thermal Protection	16,845	11.0%
Landing Gear	3,356	2.2%
Main Propulsion	22,919	15.0%
RCS Propulsion	782	0.5%
Primary Power	1,200	0.8%
Electrical Conversion and Distribution	3,233	2.1%
EHA Systems	931	0.6%
Avionics	1,702	1.1%
Thermal / Environmental Control	730	0.5%
Dry Weight Margin	19,957	13.0%
Dry Weight	153,007	100.0%
Cargo (up and down)	12,000	
Residual Propellants	1,246	
Reserve Propellants	5,869	
Landed Weight	172,122	
Entry/Landing Propellants	578	
Entry Weight	172,701	
ACS Propellants (consumed on-orbit)	1,878	
Unusable Propellants	5,743	
Insertion Weight	180,321	
Main Engine Ascent Propellants	1,137,428	
Gross Liftoff Weight	1,317,749	

<b>DIMENSIONS</b>		
Vehicle Length	159 ft	
Wingspan	92 ft	
Height (w/o gear down)	27 ft	

<b>System Gross Weight (lbs)</b>	<b>1,317,749</b>
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## SCORECARD

Number of Main Oxidizer Tanks	2
Number of Main Fuel Tanks	1
Number of Pressurant Tanks (GHe)	0
Number of OMS/RCS Oxidizer Tanks	0
Number of OMS/RCS Fuel Tanks	0
Number of Coolant Tanks	0
Number of Fuel Cell Reactant Tanks	0
Number of APU Reactant Tanks	0
Number of Water Tanks	1
<b>TOTAL NUMBER OF TANKS</b>	<b>4</b>
Number of Main Engines	2
Number of Nose RCS Thrusters	8
Number of Aft RCS Thrusters	8
Number of OMS Engines	0

## SUMMARY METRICS (in FY2003 unless otherwise noted)

<b>NON-RECURRING AND LIFE CYCLE COST</b>	
DDT&E Cost [\$M]	\$6,147 M
Acquisition Cost [\$M]	\$741 M
Life Cycle Cost [\$M] at 7 and 67 Flights/Year	\$10,396 M / \$20,776 M
Cost Per Flight [\$M/Flight] at 7 and 67 Flights/Year	\$30.58 M / \$15.50 M

## SAFETY

Loss of Mission (LOM) MFBF / Reliability	1 in 1,673 Flights / 0.99940
Loss of Vehicle (LOV) MFBF / Reliability	1 in 3,558 Flights / 0.99972
Casualty Rate [per year] at 7 and 67 Flights/Year	6.20E-04 / 2.44E-03

## OPERATIONS

GSE/Facility Cost: Non-Annualized Cost [\$M]	\$347.3 M
Fixed Operational: Annual Operations Costs [\$M]	\$80.1 M
Variable Costs per Flight [\$M]	\$4.9 M
Minimum Cycle Time / Flight Capability Per Year	7.50 days / 38.3 Flights

Table F.4. D4Ops Context 3b Metrics Summary

Weight Item	Weight [lbs]	% of Dry Weight
Tail Group	2,351	2.9%
Body Group	36,513	44.7%
Thermal Protection	9,103	11.2%
Landing Gear	1,925	2.4%
Main Propulsion	13,573	16.6%
RCS Propulsion	667	0.8%
Primary Power	1,200	1.5%
Electrical Conversion and Distribution	2,674	3.3%
EHA Systems	534	0.7%
Avionics	1,702	2.1%
Thermal / Environmental Control	730	0.9%
Dry Weight Margin	10,646	13.0%
Dry Weight	81,617	100.0%
Cargo (up and down)	12,000	
Residual Propellants	1,057	
Reserve Propellants	4,047	
Landed Weight	98,721	
Entry/Landing Propellants	332	
Entry Weight	99,053	
ACS Propellants (consumed on-orbit)	6,960	
Unusable Propellants	3,455	
Insertion Weight	109,468	
Main Engine Ascent Propellants	670,876	
Gross Liftoff Weight	780,344	

<b>DIMENSIONS</b>		
Vehicle Length	118 ft	
Wingspan	68 ft	
Height (w/o gear down)	18 ft	

<b>System Gross Weight (lbs)</b>	<b>780,344</b>
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## SCORECARD

Number of Main Oxidizer Tanks	2
Number of Main Fuel Tanks	2
Number of Pressurant Tanks (GHe)	0
Number of OMS/RCS Oxidizer Tanks	0
Number of OMS/RCS Fuel Tanks	0
Number of Coolant Tanks	0
Number of Fuel Cell Reactant Tanks	0
Number of APU Reactant Tanks	0
Number of Water Tanks	1
<b>TOTAL NUMBER OF TANKS</b>	<b>5</b>
Number of Main Engines	2
Number of Nose RCS Thrusters	8
Number of Aft RCS Thrusters	8
Number of OMS Engines	0

## SUMMARY METRICS (in FY2003 unless otherwise noted)

<b>NON-RECURRING AND LIFE CYCLE COST</b>	
DDT&E Cost [\$M]	\$4,435 M
Acquisition Cost [\$M]	\$559 M
Life Cycle Cost [\$M] at 7 and 67 Flights/Year	\$8,391 M / \$18,061 M
Cost Per Flight [\$M/Flight] at 7 and 67 Flights/Year	\$24.68 M / \$13.48 M

## SAFETY

Loss of Mission (LOM) MFBF / Reliability	1 in 1,649 Flights / 0.99939
Loss of Vehicle (LOV) MFBF / Reliability	1 in 3,502 Flights / 0.99971
Casualty Rate [per year] at 7 and 67 Flights/Year	5.88E-04 / 2.32E-03

## OPERATIONS

GSE/Facility Cost: Non-Annualized Cost [\$M]	\$194.2 M
Fixed Operational: Annual Operations Costs [\$M]	\$63.9 M
Variable Costs per Flight [\$M]	\$4.1 M
Minimum Cycle Time / Flight Capability Per Year	6.20 days / 43.4 Flights

## Appendix G – Author Biographies

### PRINCIPAL INVESTIGATOR (PI): MR. A.C. CHARANIA

Mr. A.C. Charania is senior futurist at SpaceWorks Engineering, Inc. (SEI). His previous experience includes roles at Accenture (formerly Andersen Consulting), Futron Corporation, and the Georgia Institute of Technology's Space Systems Design Laboratory (SSDL). At the first organization, projects involved formulating strategies to address future concepts of the "network" as applied to comprehensive strategic technology assessments of the terrestrial telecommunications marketplace; examining both markets (long distance, local access, Internet, Intranet, and E-Commerce) and technologies (ATM, AIN, ISDN, and xDSL). Projects at the latter two organizations included conceptual design and analysis (with a concentration on financial engineering and robust design) of future space concepts such as: Space Solar Power for NASA Marshall, Mars Orbit Basing (MOB) / Solar Clipper for NASA HQ, 3rd Gen and Bantam RLVs for NASA Marshall, space tourism for NASA Langley, Phobos landers, and Europa landers. In particular, his expertise includes far term technology / market forecasting utilizing analytical models and incorporation of robust design methods in the conceptual design process. He is a previous NASA Institute for Advanced Concepts (NIAC) fellow based on his role as Principal Investigator for the phase I study (CP-01-02) entitled: "Networks on the Edge of Forever: Meteor Burst (MB) Communication Networks on Mars." He holds an M.S. in Aerospace Engineering from the Georgia Institute of Technology (with a concentration in systems design and optimization), a B.S. in Aerospace Engineering from the Georgia Institute of Technology, and a B.A. in Economics/Mathematics from Emory University.

Selected professional papers include:

- Charania, A., Olds, J., "Application of the Abbreviated Technology Identification, Evaluation, and Selection (ATIES) Methodology to a Mars Orbit Basing (MOB) Solar Clipper Architecture," IAC-02-U.5.01, 53rd International Astronautical Congress, The World Space Congress - 2002, Houston, Texas, October 10-19, 2002.
- Charania, A., Bradford, J. E., Olds, J., Graham, M., "System Level Uncertainty Assessment for Collaborative RLV Design," JANNAF-2002-2B-4-MSS, 2002 JANNAF 38th Combustion Subcommittee/26th Airbreathing Propulsion Subcommittee/20th Propulsion Systems Hazards Subcommittee/2nd Modeling and Simulation Subcommittee Joint Meeting, Destin, Florida, April 8-12, 2002.
- Charania, A.C., Crocker, A., Olds, J., Bradford, J., "A Method For Strategic Technology Investment Prioritization For Advanced Space Transportation Systems," IAF-01-U.2.06, 52nd International Astronautical Congress, Toulouse, France, October 1-5, 2001.
- Crocker, A., Charania, A.C., Olds, J., "An Introduction to the ROSETTA Modeling Process for Advanced Space Transportation Technology Investment," AIAA-2001-4625, Space 2001 Conference and Exposition, Albuquerque, NM, August 28-30, 2001.
- Charania, A.C., Tooley, J., Cowart, K., Sakai, T., Salinas, R., Sorensen, K., St. Germain, B., Wilson, S. "Mars Scenario-Based Visioning: Logistical Optimization of Transportation Architectures." Presented at the 1999 Mars Society Conference, Boulder, CO, August 12-15, 1999.

### CO-PRINCIPAL INVESTIGATOR (CO-PI): MR. JON WALLACE

Mr. Jon Wallace is a Project Engineer at SpaceWorks Engineering, Inc. (SEI) in Atlanta, Georgia. His background includes experience with conceptual design and evaluation of advanced aerospace systems. During his academic tenure, he served as team leader for the conceptual design of an in-space tether launch system intended to support Mars exploration. His experience includes trajectory optimization for future generation RLVs, CAD geometry automation and optimization, and historical evaluation of nuclear electric propulsion concepts. He holds a B.S. in Aerospace Engineering from the Georgia Institute of Technology.

Selected professional papers include:

- Wallace, J., J.R. Olds, A.C. Charania, and G. Woodcock, "A Study of ARTS: A Dual-Fuel Reusable Launch Vehicle with Launch Assist", AIAA-2003-5269, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July, 2003.

#### **OTHER PERSONNEL: DR. JOHN OLDS**

Dr. John R. Olds is President and CEO of SpaceWorks Engineering, Inc. Dr. Olds has over 15 years of experience working on advanced space transportation projects, having worked with General Dynamics' Space Systems Division, NASA Langley Research Center, NASA Marshall Space Flight Center, and the Mars Mission Research Center at North Carolina State University. Dr. Olds is also currently an associate professor in the School of Aerospace Engineering at Georgia Tech where he acts as Director of the Space Systems Design Laboratory. As Director of the SSDL, he has had the opportunity to advise numerous M.S. and Ph.D. students on space-oriented design topics. He is author or co-author of over 50 technical papers related to conceptual design of advanced space systems since 1986. He has conducted studies of advanced launch systems, RLV designs, Mars missions, LEO-based satellite constellations, lunar resource missions, and space solar power satellites. Dr. Olds is a registered professional engineer in the state of Georgia and an Associate Fellow of the American Institute of Aeronautics and Astronautics. He holds a Ph.D. in Aerospace Engineering from N.C. State University, an M.S. in Aeronautics and Astronautics from Stanford University, and a B.S. in Aerospace Engineering from N.C. State University.

Selected professional papers include:

- Marcus, L., Way, D., Medlin, M., Sakai, T., McIntire, J., Olds, J., "Technology Assessment for Manned Mars Exploration Using a ROSETTA Model of a Bimodal Nuclear Thermal Rocket (BNTR)," AIAA 2001-4623, AIAA Space 2001 Conference and Exposition, Albuquerque, New Mexico, August 28-30, 2001.
- Budianto, I., Olds, J., "A Collaborative Optimization Approach to Design and Deployment of a Space Based Infrared System Constellation," IEEE P335E, 2000 IEEE Aerospace Conference, Big Sky, MT, March 18-25, 2000.
- Charania, A.C., Olds, J., "A Unified Economic View of Space Solar Power (SSP)." IAF-00-R.1.06, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.
- Olds, J., Way, D., Budianto, I., Charania, A.C., Marcus, L., "In-Space Deployment Options for Large Space Solar Power Satellites", IAA-00-R.2.02, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.
- Olds, J., McCormick, D., Charania, A.C., Marcus, L., "Space Tourism: Making it Work for Fun and Profit." IAA-00-IAA.1.3.05, 51st International Astronautical Congress, Rio de Janeiro, Brazil, October 2-6, 2000.

#### **OTHER PERSONNEL: DR. BRAD ST. GERMAIN**

Dr. Brad St. Germain is Director of Concept Development at SpaceWorks Engineering, Inc. (SEI). While at the Space Systems Design Lab at the Georgia Institute of Technology, he developed optimization technique for the performance and powerhead configuration of liquid rocket engines (Ph.D. Thesis), led various conceptual level launch vehicle and space systems design projects, and supported other research projects with propulsion/trajectory/weights & sizing analysis. While working at Pratt & Whitney Space Propulsion (West Palm Beach, FL), he evaluated propulsion options for low cost next generation launch vehicle using POST-3D and CONSIZ, worked on tri-propellant liquid rocket engine expander cycle model using ROCETS, analyzed propulsion options for conceptual bimese launch vehicle concept, and constructed a database of historical hydrocarbon booster mass fractions. While working at the NASA Marshall Space Flight Center, performed trade studies involving small payload class two-staged-to-orbit rocket-based combined cycle launch vehicle. While working at the NASA Langley Research Center (LaRC) Vehicle Analysis Branch (VAB) he performed trajectory optimization of KLIN cycle powered all-rocket winged body reusable launch vehicles. Dr. St. Germain holds Doctoral and Masters degrees in Aerospace Engineering from the Georgia Institute of Technology. He also holds a Bachelor of Science degree in Mechanical Engineering from Louisiana State University.

Selected professional papers include:

- St. Germain, B., Kokan, T., Marcus, L., Miller, J., Rohrschneider, R., Staton, E., Olds, J., "Tanker Argus: Re-supply for a LEO Cryogenic Propellant Depot," IAC-02-V.P.10, 53rd International Astronautical Congress, The World Space Congress - 2002, Houston, Texas, October 10-19, 2002.
- St. Germain, B., Olds, J., McIntire, J., Nelson, D., Weglian, J., Ledsinger, L., "Starsaber: A Small Payload-Class TSTO Vehicle Concept Utilizing Rocket-Based Combined Cycle Propulsion," AIAA 2001-3516, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference And Exhibit, Salt Lake City, Utah, July 8-11, 2001.
- St. Germain, B. D., Olds, J. R., "An Evaluation of Two Alternate Propulsion Concepts for Bantam-Argus: Deeply-Cooled Turbojet+Rocket and Pulsed Detonation Rocket+Ramjet," AIAA 99-2354, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999.

## Appendix H – List of Acronyms

$\Delta V$	Delta V
AATE	Architecture Assessment Tool
ACS	Attitude Control System
AHP	Analytic Hierarchic Process
APU	Auxiliary Power Unit
CABAM	Cost And Business Assessment Module
CA	Contributing Analysis
CDF	Cumulative Distribution Function
CER	Cost Estimating Relationship
CES	Crew Escape System
D4OPS	Design For Operations
DOE	Design Of Experiments
DDT&E	Design, Development, Testing, And Evaluation
DSM	Design Structure Matrix
EC	Engineering Characteristics
ECLSS	Environmental Control and Life Support System
EDO	Extended Duration Orbiter
EELV	Evolved Expendable Launch Vehicle
EHA	Electro-Hydrostatic Actuator
EMA	Electro-Mechanical Actuators
ETO	Earth To Orbit
FALCON	Force Application and Launch from CONUS (Continental United States)
FBS	Functional Breakdown Structure
FOM	Figure of Merit
GEN 3	3rd Generation
GLOW	Gross Lift-Off Weight
IOC	Initial Operating Capability
ISP	Specific Impulse
ISP_BAR	Average Propulsive Isp Without Losses
ISS	International Space Station
ISTP	Integrated Space Transportation Plan
IVHM	Integrated Vehicle Health Monitoring
KSC	Kennedy Space Center
LaRC	Langley Research Center
LCC	Life Cycle Cost
LEO	Low Earth Orbit
LRU	Line Replacement Unit
MADAM	Multiple Attribute Decision Making
MDO	Multi-Disciplinary Design Optimization
MER	Mass Estimating Relationship
MM	Morphological Matrix
MPS	Main Propulsion System
MSFC	Marshall Space Flight Center
MTBF	Mean Time Between Failure
MTBR	Mean Time Between Repair
NAFCOM	NASA-Air Force Cost Model
NGLT	Next Generation Launch Technology
OE	Operational Effectiveness
OEC	Overall Evaluation Criteria
OML	Outer Mold Line
OMS	Orbital Maneuvering System
OPF	Orbiter Processing Facility

ORS	Operationally Responsive Spacelift
OSP	Orbital Space Plane
PDF	Probability Density Function
PEM	Pugh Evaluation Matrix
POST	Program To Optimize Simulated Trajectories
QFD	Quality Function Deployment
RBCC	Rocket-Based Combined Cycle
RCA	Root Cause Analysis
RCADB	Root Cause Analysis Database
RCS	Reaction Control System
RLS	Reusable Launch System
RLV	Reusable Launch Vehicle
ROM	Rough Order Of Magnitude
SRB	Solid Rocket Booster
SEI	SpaceWorks Engineering, Inc. (SEI)
SOP	State of Practice
SPST	Space Propulsion Synergy Team
SSTO	Single Stage To Orbit
STS	Space Transportation System
T/W	Thrust To Weight Ratio
TAT	Turn Around Time
TFU	Theoretical First Unit
TOPSIS	Technique For Order Preference By Similarity To Ideal Solution
TPS	Thermal Protection System
TSTO	Two Stage To Orbit
VAB	Vehicle Assembly Building
W&S	Weights And Sizing
WBS	Weight Breakdown Structure
WS	Weighting Scenario

# Production Notes

## CREDITS

This project was completed by SpaceWorks Engineering, Inc. (SEI) with most major personnel contributing to the requirements gathering, development, analysis, and documentation of the project deliverables and the final report.

## PRODUCTION NOTES

This manual was created electronically using Microsoft Word and Adobe Acrobat. Graphic art was produced using Adobe Photoshop and Denaba Canvas. CAD images were captured from Solid Edge V14. Times Roman, Arial Narrow, and Arial typefaces are used throughout this book.